COMMERCIALIZATION OF BIOMASS COFIRING WITH COAL IN STOKER BOILERS

by

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ABSTRACT

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Many special cases of cofiring biomass with coal has been examined in the past, with the growing concern for global climate change, it is now time to demonstrate its feasibility in practical use. Since 1997, the Engineering Program of Biomass Energy at the University of Pittsburgh has conducted a series of demonstrations, which focused on the utilization of clean urban waste in stoker boilers. In this paper, two demonstrations of cofiring biomass (clean urban waste wood) with coal in stoker boilers, conducted recently in the Bellefield Boiler Plant and the NIOSH boiler plant are described and the results summarized, including engineering and economic studies, parametric testing, and examining the feasibility of commercialization.

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1.0 INTRODUCTION

Biomass cofiring is gaining more attention as the greenhouse effect and the need for energy continue to grow. Cofiring biomass with coal in steam and power boilers will effectively reduce greenhouse gas emissions, provide energy diversity/security and improve local economies. The technologies developed by Department of Energy and various technological institutes and universities has brought biomass energy closer to being economically competitive with conventional alternatives. The critically needed next steps are continued technical progress in conversion efficiency, construction of a series of integrated demonstration facilities that will give farmers, processors and operators the confidence to build this new American industry.

There have been some demonstrations of biomass cofiring with coal in pulverized coal (PC) and cyclone boilers by electricity generating utilities, but none in industrial stoker boilers. However, industrial boilers, though significantly smaller in general than those operated by utilities, generate a significant amount of steam throughout the United States. Over 1,000 of these industrial systems and possibly as many as 2,000 – are coal-fired stoker boilers, with the rest being primarily gas-fired. Most of the stoker boilers are quite old and many of them are under some pressure to improve their reliability and their emissions. [1]

In response to the needs to (1) implement the use of biomass alternatives to fossil fuels for mitigating emission of greenhouse gases or air pollutants like NOx and SO_2 and (2) find a market for biomass that would otherwise be landfilled or openly burned, the Engineering Program for Biomass Energy at the University of Pittsburgh has been investigating opportunities to co-fire biomass in Pittsburgh-area stoker boilers. In March and April 2001, two demonstrations were conducted to study the effect of cofiring of urban demolition and construction wood with coal on stoker boiler operation, the environment, and the economy. One demonstration was conducted in one of the stoker boilers at the Bellefield Boiler Plant (BBP) in the Oakland District of Pittsburgh; the other was conducted in the boiler plant operated by the National Institute of Occupational Safety and Health (NIOSH) in the south hills of Pittsburgh.

1.1 Biomass

Biomass is organic matter, either raw or processed. Put another way, biomass is stored solar energy that can be converted to electricity or fuel. It begins as energy from the sun, and then is stored in plants through photosynthesis. The capture of solar energy as fixed carbon in biomass via photosynthesis, during which carbon dioxide (CO_2) is converted to organic compounds, is depicted by the equation:

$$CO_2 + H_2O + light \xrightarrow{chlorophyll} (CH_2O) + O_2$$

Carbohydrate, represented by the building block (CH_2O), is the primary organic product. The direct capture efficiency of the incident solar radiation in biomass has been estimated to range from about 8% to as high as 15%, but under most operational conditions in the field, it is generally in the 1% range or less. However, the global energy potential of virgin biomass is very large. It is estimated that the world's biomass, which could be harvested and used as a renewable energy resource, is about 100 times the world's total annual energy consumption. [2]

The major categories and types of biomass fuel used in the United States today include [3]

- Wood processing residue
    - Sawdust and paper trash
    - Tree prunings and yard clippings

- In-forest residues
    - Clearance wood
    - Dead/doomed trees
    - Excess timber
- Agriculture residues
    - Corn stover
    - Rice straw and wheat straw
    - Used vegetable oils

- Urban wood residues:
    - Construction and demolition wood
    - Wood and brush from land clearing
    - Wood waste from the manufacturing of cabinets, furniture and other wood products
- Grown biomass
    - Switchgrass
    - Hybrid poplars

In the two cofiring demonstrations conducted at BBP and NIOSH, the project group used construction and demolition wood, which are the wooden components of the debris generated during construction, renovation and demolition of buildings, roads and other structures.

1.2 Benefits of the Use of Biomass

There are several ways of extracting biomass energy: combustion, gasification, pyrolysis, and fermentation; for demolition and construction wood, burial in landfill is the most common method employed. [1]

More than any other resource, biomass, when combusted, is capable of simultaneously addressing the nation's energy, environmental and economic needs. Specifically, the benefits from the use of biomass are (1) reducing emissions, (2) reducing the pressure on landfills (3) providing energy diversity/security, and (4) improving the local economy, including adjusting land use patterns in agricultural areas.

1.2.1 Benefits to the Environment

There is globe-wide concern about the enhanced greenhouse effect which results from a gradually increasing concentration of CO_2, CH_4 and other gases, which are generated from burning fossil fuel such as coal, oil and natural gas. Over the past fifty years, production of carbon dioxide, nitrogen oxides and methane has risen sharply. Figure 1[4] shows how much each gas contributes to the greenhouse effect. Scientists are busy with developing new energy sources that don't emit greenhouse gases into the atmosphere. Biomass is one such alternative, which will greatly contribute to improvement of the environment, primarily by reducing the emissions of greenhouse gases, air pollutants and particulates.

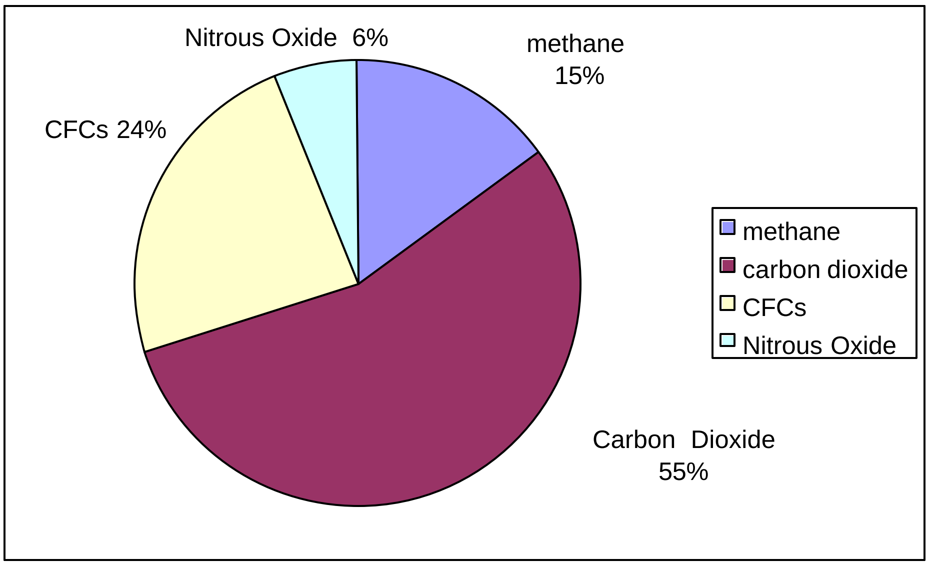


Figure 1 Contribution of each greenhouse gas to the greenhouse effect

1.2.1.1 <u>Reducing Greenhouse Gas Emissions.</u> Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and the chlorofluorocarbons (CFCs), which absorb infrared radiation and inhibit the radiative cooling of the earth and therefore contribute to global-warming, are called greenhouse gas. Since 1800, 220 to 250 pentagrams (10^{15} grams) of carbon from fossil reserves (250 billion tons) are estimated to have been released into the atmosphere as CO_2. This fossil carbon has increased the atmospheric concentration of CO_2 by 30%. Presently, 6½ to 7 billion tons of fossil carbon is added to the atmosphere each year [5]. Data from The United Nations–sponsored Intergovernmental Panel on Climate Change suggests that the 0.3 °C to 0.6 °C global warming observed in this past century has been caused by the built-up of these greenhouse gases, and another 3.5°C will be gained if the current increase in emission rates of these gases are maintained in the next century [5]. Figure 2 shows the temperature change in the past century.

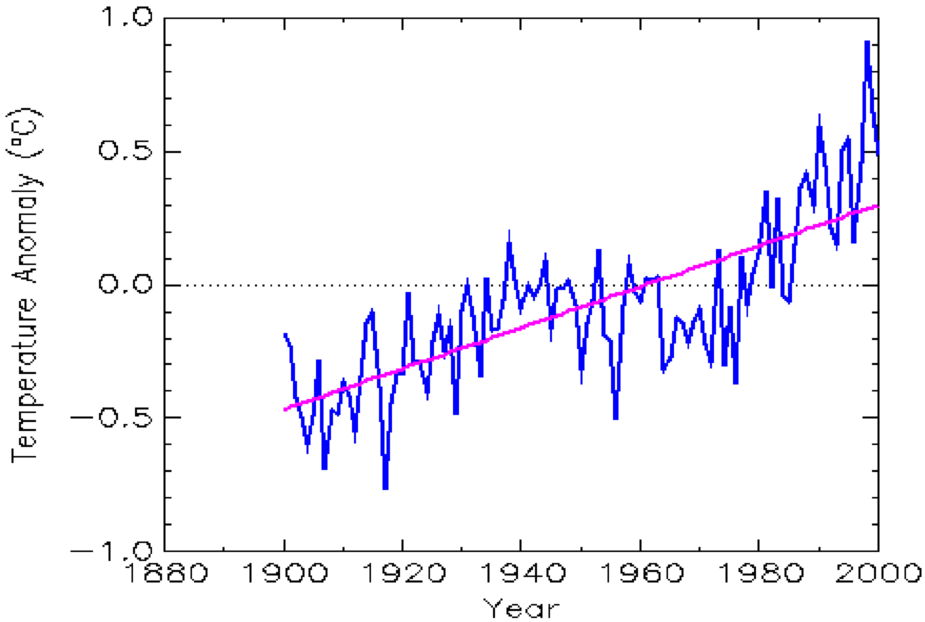


Figure 2 1900-2000 Temperature Time Series

The production (mining) of a fossil fuel removes carbon that is stored underground and transfers it to the atmosphere. When biomass is grown sustainably, the carbon emitted when it is combusted for energy is recycled back into growing new trees or other crops at roughly the same rate (i.e., over tens of years, not millions of years), thus contributing a net zero loading to the CO_2 in the atmosphere. Thus, the fossil fuel displaced by biomass represents a net reduction in the amount of new carbon being transferred to the atmosphere from underground. [6]

1.2.1.2 Reducing the Emissions of NOx and SOx. The combustion of biomass will also reduce the emission of the air pollutants like sulfur oxides (SOx) and possibly nitrogen oxides (NOx). The amount of SOx emitted from an uncontrolled smoke stack is directly proportional to the amount of sulfur contained in the fuel. Since almost all biomass contains little or no sulfur, less SOx will be released into atmosphere during biomass burning compared to normal fossil fuel burning.

NOx is mainly produced from the oxidation of (1) the nitrogen contained in the fuel (fuel–NOx) and (2) the nitrogen in the combustion air (thermal–NOx). Because almost all biomass contains less nitrogen than most fossil fuels, there is almost always less fuel-NOx emission from biomass fuel burning. Thermal-NOx depends on not only the initial concentrations of NO formed during combustion (which is related to the combustion temperature), but also on the fluid dynamics in the flame. Demonstrations conducted on some PC boilers have showed the possibility of a reduction of NOx from the cofiring of biomass fuel.

1.2.1.3 Reducing the Emissions of Particulates. Co-firing wood with coal in stoker boilers is a relatively new technology and there are no literature references that speak directly to the prediction of particulate production under these conditions. What is known about the combustion of wood, coal, and wood-coal mixtures implies that there will be a reduction in particulate emissions while co-firing wood with coal. Here are three observations: (1) An EPA guide for estimating emissions from stationary sources indicates that, calculated as pounds of particulate emissions per ton of fuel combusted, a boiler burning wood on a traveling grate will emit less than half the particulates as will a traveling grate boiler burning coal.[7] (2) Literature on the co-firing of wood with coal in pulverized coal boilers indicates a decrease in particulate emissions. [8,9] (3) David Tillman, Manager, Utility and Energy programs, Foster Wheeler Environmental Corporation and consultant to the Electric Power Research Institute (EPRI) biomass research programs, has indicated that he would expect a decrease in particulate emission from the co-firing of wood with coal in the type of traveling grate stoker boilers being investigated in Pittsburgh. [1]

1.2.2 Benefits to Waste Disposal

The major categories of disposal options for biomass residues if not used as cofiring fuel include: [3]

- Open burning of agricultural and forestry residues
- Landfill disposal of waste wood
- Composting and land application of waste wood
- Land spreading of wood chips and bark as mulch and cover

- In-forest accumulation of residues as downed and over-growth material

Each of these methods of disposing waste contributes to increasing the concentration of CO_2 and CH_4 in the atmosphere. For urban wood waste, the traditional disposal option is burial in landfill. This (a) occupies scarce landfill space, (b) adds another cost to the wood product, and (c) adds their carbon content upon decomposition into CO_2 and CH_4 to the atmosphere. As the materials of waste wood degrade, CH_4 and CO_2 are emitted in about equal quantities. Actually CH_4 is more reactive as a greenhouse gas, by a factor of about 25 times per unit of carbon (IPCC 1996); hence it is more harmful to the environment. In addition, waste wood burial is also a source of water-pollution. Application of waste wood otherwise landfilled will effectively reduce the pressure on landfills.

1.2.3 Benefits to Energy Diversity/Security

Use of biomass fuels obviously will offer an alternate and valuable resource in the face of energy deficits. Especially in case a major supply disruption happens, it will take an irreplaceable position. In the United States, for instance, these techniques could increase biomass' share of energy production to more than 20 percent of the country's energy requirements.

On the other hand, use of biomass fuels will enhance energy security. Energy from biomass combustion could economically replace 50% or more of that from the United States' entire current level of gasoline consumption.

1.2.4 Benefits to the Economy

Because biomass feedstocks need to be planted, collected, processed and transported, a local industry will be developed involving planting, collecting, processing and transportation in this field. That means jobs are created and employment is increased. Farmers will have interests to plant and harvest the agricultural and crops that could be grown, thus seeing their income rise. The U.S. Department of Agriculture estimates for example that 17,000 jobs are created per every million of gallons of ethanol produced from corn, and the Electric Power Research Institute estimates that producing 5 quadrillion

Btu's of electricity on 50 million acres of land world increase overall farm income by $12 billion annually (the U.S. consumes about 90 quadrillion Btu's annually) [10]. So doing would encourage more individuals to remain in rural areas and provide incentives to prevent farm ringing sites to be converted to suburban housing and commercial uses.

2.0 BIOMASS COFIRE PROGRAM AT THE UNIVERSITY OF PITTSBURGH

In 1996, the Northeastern Area State & Private Forestry Program of the USDA – Forest Service initiated a three-year program with the University of Pittsburgh to demonstrate wood/coal cofiring for stoker and fluid-bed boilers in western Pennsylvania. The prime objective of the University of Pittsburgh's overall wood/coal cofiring program is the successful introduction of commercial cofiring of urban wood wastes for stoker boilers in western Pennsylvania. The first project, conducted in 1997, under this program was a demonstration at the traveling-grate stoker boiler of a local industrial firm, the Pittsburgh Brewing Company. In May 1999, a second demonstration was completed at a federally-owned spreader stoker boiler plant operated by the National Institute for Occupational Safety & Health (NIOSH) in Pittsburgh. By these two demonstrations, the University learned much about the problems associated with seeking specific sources of urban waste wood, its processing into boiler fuel, and the ability of stoker boiler plants to receive and fire wood/coal blend. [1]

Based on these previous experiences, the objectives of the demonstrations conducted in March and April 2001 at Bellefield Boiler Plant and NIOSH were: (a) determining an acceptable method of processing, (b) determining the optimal blending ratio of wood to coal, and (c) evaluating the feasibility of cofiring. In these demonstrations, a number of issues were addressed: [1]

- Can a properly flowable blend be identified for feeding the BBP and NIOSH boiler plants?
- Can clean, segregated construction/demolition wood be included in the urban waste wood to be used as the commercial feed for the NIOSH and BBP boiler plants?
- Will the emissions during combustion of wood/coal blends containing construction/demolition wood meet regulations?
- Can a sufficiently large source of permittable urban waste wood be identified to provide a commercial feed for the BBP and NIOSH boiler plants?
- Can the waste wood from this source be economically and contractually included in a commercial feed for the NIOSH and BBP boiler plants?

3.0 DEMONSTRATION DESCRIPTION

3.1 Goals of the Demonstration

3.1.1 Determining an Acceptable Method of Processing

Wood collected for co-firing is urban waste wood including construction wood and demolition wood. Desirable wood for cofiring is dry, low in fines content and chip-shaped. The most important characteristics of wood as it relates to its use as a fuel in stoker boilers are:

- **Moisture content**

The moisture content for freshly harvested "green" wood is approximately 50%. Over time the moisture content declines to between 5% and 15%. The high moisture content of green wood poses several problems: (a) it will increase the transportation and handling cost and; (b) it will increase the volume of flue gas generated in combustion, requiring an increase in draft fan output; (c) it will absorb the heat from fuel combustion and reduce the boiler efficiency; (d) it will promote the fines contained in the fuel to cling together to form large particles which reduce the flowability of the fuel.

- **Particle size and shape**

Stoker boilers are designed for a given fuel size distribution. Increasing the top size will increase the burnout time and the potential for unburned or still burning fuel from passing forward into the ash pit. Higher aspect ratios and frayed ends(such as found in tub-ground, mulch-like material) increase the chances for bridging. Wood has a higher heat release rate so that the top size may be increased above the allowable size for coal, but wood also has a heightened possibility for bridging.

These demonstrations were designed to examine what size and shape of wood is suitable for conveyance and combustion. A wood/coal fuel blend needs to be conveyed from the mixing point onto the grate without flow stoppage or fuel segregation and without plant modification and capital expenditure.

Another aspect of the demonstrations was to determine the maximum moisture content of the wood that doesn't decrease the efficiency of the boiler greatly or cause trouble in fuel conveyance. Additionally, too much fine production from processing is undesirable. When exposed to moisture, fines can cling together to become big agglomerates, which need some extra labor to get through the delivery grill of the boiler plant.

Based on the above criteria, important decisions from the demonstration are: (a) how to process wood; (b) which company will process the wood commercially in the Pittsburgh region; and (c) which kind of blending machines should be used to blend the wood with coal. The mixing of the wood and coal must be reasonably complete to make the mixture homogeneous and flowable. Otherwise an occasional exception in concentration of wood or coal comes through the stokers and the boiler operators have to adjust the boiler parameters to compensate.

3.1.2 Determining the Optimal Blending Ratio of Wood to Coal

During each demonstration the heat input from wood was varied as much as possible to seek the optimal blending ratio of construction wood and demolition wood to coal in the spreader stoker boiler at the NIOSH boiler plant and the traveling grate stoker used in the demonstration at the Bellefield Boiler Plant. Emissions reductions were measured at all ratios.

3.1.3 Co-firing Feasibility

During each demonstration, inspection was made of the fuel conveyance, fuel burning, steaming rate, combustion efficiency, and equipment performance. A main goal of the project was to determine if without modification and capital expenditure to the boiler plant, co-firing would meet the requirement for heat, would bring no harm to the equipment and its operation, and would be safe.

3.2. Fuel Preparation

3.2.1 Wood

The wood fuels used in the demonstrations at BBP and NIOSH were: (1) clean, source-segregated construction wood and (2) demolition wood, which generally are the wooden components of the debris generated during construction, renovation and demolition of buildings, roads and other structures [10] . 40% of all new residential construction residues consist of wood and wood products. The amount of wood in demolition debris generally varies from 15% to 85%.

Construction wood, used at both BBP and NIOSH, was either framing wood waste from a condominium construction site or trim-ends from a truss manufacturing plant. Demolition wood, which was used only at NIOSH, consisted of roof joists and attached decking from the demolition of public housing project apartment buildings located in the city of Pittsburgh (Picture 1).

Picture 1 Demolition Wood

3.2.1.1 Wood Source. **Construction wood:** In mid-November 2000, Thompson Properties delivered five tons of construction wood waste to the J.A. Rutter Company (JARC). The wood had been collected in roll-off containers at a condominium construction site being developed by Thompson Properties in a northern suburb of Pittsburgh. The wood was mixed with about 30% plywood and particleboard. In mid-December 2000, Seven D Corporation, the roof truss manufacturer in Tyrone, PA, delivered two trucks loads of construction wood to Emery Tree Service (ETS). The wood consisted of trim-ends up to several feet long.

Demolition wood: J.A. Rutter Company and Emery collected the demolition wood at a public housing site of the city of Pittsburgh in Arlington Heights, and transferred the wood to the same terminal which stores the coal for boiler plants.

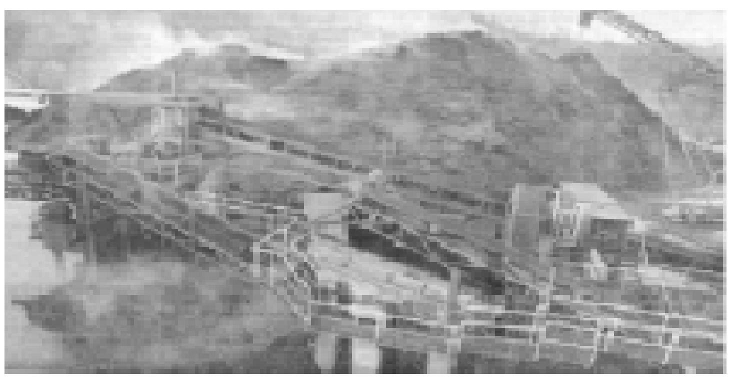
3.2.1.2 Wood Processing. **Construction Wood:** The construction wood was processed by both JARC and ETS. JARC used a tub grinder (Picture 2) to process 5 tons of the construction site's framing waste, and ETS used a three-stage hammermill to process 5 tons of the truss manufacturing trim-ends.

The screens of the tub grinder were adjusted to produce the most cubic and least "mulch-like" material possible from the framing wood waste. This fuel had a top size of three inches and a bottom size of zero. The most cubic wood produced by the tub grinding had a length to width to depth ratio of approximately 6:1:1 with most of the wood having ratios of 8:1:1 or more. The fuel contained a few pieces up to six inches long and contained a high fraction of sawdust-like material (<1/4 inch length). The ground wood was not as good as expected- - more fines than anticipated were produced, principally from the particleboard, however the larger pieces contained far fewer lengthy spears than previous grinds. (Picture 3)

Picture 2 Tub grinder

Picture 3 Tub Ground Construction Wood

ETS used its three-stage hammermill (Picture 4) to produce a 3 inches by 0 inches (3"x0") cofiring fuel with a maximum length to width to depth ratio close to 4:1:1. This aspect ratio was more consistent than that obtained with the tub grinded wood. Also this material had fewer pieces that were longer than three inches, and it contained less fines because of screen separation after each stage.



Picture 4 Hammermill

Demolition Wood: Both the tub grinder of JARC and hammermill of ETS were used to process the demolition wood. Using the same screen setting used for construction wood, the tub grinding of the demolition wood produced a material with a smaller top size and many more fines (Picture 5). With minor adjustments, the hammermill produced a material from the demolition wood that contained fewer fines and had a more consistent aspect ratio than was produced from the construction wood.

Picture 5 Tub Ground Demolition Wood

The project team concluded that the products of demolition wood processed by the hammermill of ETS were superior to that processed by the tub grinder at JARC. It contained less fines and had a more consistent aspect ratio.

3.2.1.3 Wood Delivery. After processing, the wood was trucked to the coal terminals: MonValley T Company (MVTC) for Bellefield boiler plant and Three Rivers Marine and Rail Company (TRMRC) for NIOSH boiler plant.

3.2.2 Coal Fuel

The coal fuel used in the test burns was the same fuel used by each boiler plant in its normal operations. The coal used in preparing for the NIOSH boiler plant was unloaded at Three Rivers Marine and Rail Company Terminal at Belle Vernon, PA, The coal used in preparing for the BBP was unloaded at the MonValley T Company in Glassport, PA and stored on the ground next to the wood pile. Appendix 2 and 3 gives the analysis of coal used in the tests of NIOSH and BBP.

3.2.3 Fuel Blending

In previous demonstrations conducted by program group, several methods of blending wood with coal had been tested and its effect of each blend on conveyance system of boiler was determined. The methods were: 1. Mixing on the ground with a front-end loader (Picture 6) 2. Layering on bed of delivery truck (Picture 7) 3. Mixing in a FECON mixing-hopper with two front-end loaders (Picture 8).

Picture 6 Fuel mixing on the ground

Picture 7 Fuel mixing on bed of delivery truck

Picture 8 Fuel Mixing in a FECON mixing-hopper with two front-end loaders

- **BBP**

At the MVTC terminal, the clean construction wood was blended with coal using single front loader and a FECON blender with a 7.5m3 hopper. On the night before the blending, the temperature fell below -12 °C and both the coal and wood piles had become frozen. The coal and wood were layered into new piles at the desired ratios with the front-end loader and turned several times to break up the large frozen lumps. These piles were then loaded into the blender and four final blend piles with the volume equivalent of 60-tons of coal were made: one pile at a coal to wood volume ratio of 4:1(20% wood), one at a ratio of 2:1 (33% wood) and two piles at a ratio of 3:2 coal to wood (40% wood). Each pile was loaded into a 7—ton railcar and shipped to BBP when called.

- **NIOSH**

At the TRMRC terminal neither the coal pile nor the wood pile became frozen. The fuel blends were prepared by mixing on the ground with a front-end loader. Six truckloads of blend were prepared. Three fuel blends were prepared: 20 % construction wood by volume, which was used to establish the leading characteristics of the blend's through the receiving grill; 33% demolition wood by volume; 33% construction wood by volume. Each truck-load was delivered to boiler plant by tri-axle truck when called. The blends are summarized in Table 1.

3.2.4 Delivery to the Boiler Plants

- **NIOSH**

The fuel blend was loaded into 24-ton tri-axle trucks, delivered to NIOSH, then dumped onto the receiving grill (picture 9)

- **BBP**

The fuel was blend loaded into 70-ton CSX railcars, delivered to BBP, then bottom dumped into the receiving hopper. We found that, for the blend fuel containing only 20% wood there was conveyance problem, but there was problems when the blend fuel contained 33% or 40% wood. (Picture 10)

Picture 9 Fuel dumping in NIOSH

Picture 10 Fuel dumping in BBP

Table 1 shows the distribution of C/D wood used at both BBP and NIOSH boiler plants. It could be seen that both demolition wood cofiring (33% by volume) and construction wood cofiring (33% wood) were conducted in NIOSH boiler plant, whereas only construction wood cofiring (20%, 33% and 40% by volume respectively) was implemented in Bellefield boiler plant.

Table 1 Distribution of C/D wood used at both BBP and NIOSH boiler plants

Type of Wood	Construction Wood						Demolition Wood	
Type of Processing Machine	Tub Grinder(Rutter)				Hammermill (Emery)		Tub Grinder (Rutter)	Hammermill (Emery)
Wood content in Blend (by volume)	20%	33%		40%	20%	33%	33%	33%
Demonstration boiler	BBP	BBP	NIOSH	BBP	BBP	NIOISH	NIOSH	NIOSH

3.3 Demonstration in the NIOSH Boiler Plant

3.3.1 NIOSH Boiler Plant

The NIOSH Boiler Plant supplies steam for a district heating system that services the majority of the buildings on the old Bureau of Mine's site in Bruceton, PA. The site currently houses the NIOSH Bruceton Research Center, the National Energy Technology Laboratory of the U.S. Department of Energy and U.S. Department of Labor's Pittsburgh Mine Safety and Health Administration Technology Center.

The boiler house contains two gas-fired boilers and a Keeler spreader stoker boiler. The stoker boiler is rated at 55,000 PPH at 200 psig (but normally operates at 100 psig) with a baghouse for particulate control. The Allegheny County Health Department (ACHD) has primacy for air quality assurance at the boiler plant and requires the use of low-sulfur compliance coal.

The junior pea stoker coal comes by barge from eastern Kentucky to the Three Rivers Marine and Rail Company near Belle Vernon, PA, a long open transfer station on the east bank of the Monongahela River. The fuel blend is trucked from the transfer station to the plant in 25-ton loads. Fuel is dumped directly into a receiving hopper. The fuel-receiving hopper is situated below a steel grate with openings a minimum of 5" by 8". The hopper has a capacity of 10 to 12 tons of coal. A Syntron fuel feeder picks up the fuel onto a belt conveyer, which takes the fuel up an elevation of 20 feet to a bucket elevator. The fuel feeder has a vibrator to keep the fuel from clogging, and there is an overhang magnet to collect metal pieces. There is also a magnet in the downloader to the bucket elevator. The elevator raises the fuel six stories to hoppers. From these hoppers the coal goes down through 2' by 1' ducts onto a horizontal paddle conveyer, which unloads the fuel into an unsegregated, 600-ton capacity bunker. There are twelve gates at the bottom of the bunker. Another horizontal conveyer receives the fuel from any one of the selected gates and delivers the fuel to the Detroit Roto Grate stoker spreader feeder system.
There are three 18" feeders each with a capacity of 500 to 2000 pounds of coal per hour. The stokers throw the coal to the back of the boiler, while a moving grate travels from back to front. The fuel burns both above the grate in suspension and on the grate.

A large number of fuel particles leave unburned from the firebox in the combustion gas. The finer of the unburned particles go through the economizer and are collected in the baghouse with the fly ash. The larger ones settle out in an expansion vessel above the boiler and are reinjected into the boiler by a stream of over-fire air. Doing so completes their combustion, thus improving efficiency and preventing still-burning sparklers from entering the baghouse. The two-reinjection lines enter on each side of the boiler slightly above the grate. The bottom ash falls into a hopper. This ash is removed periodically by a vacuum system. The ultimate fly ash is collected in a bag-house. Figure 3 is a schematic flow diagram of fuel conveyance system and Figure 4 is a diagram of boiler.

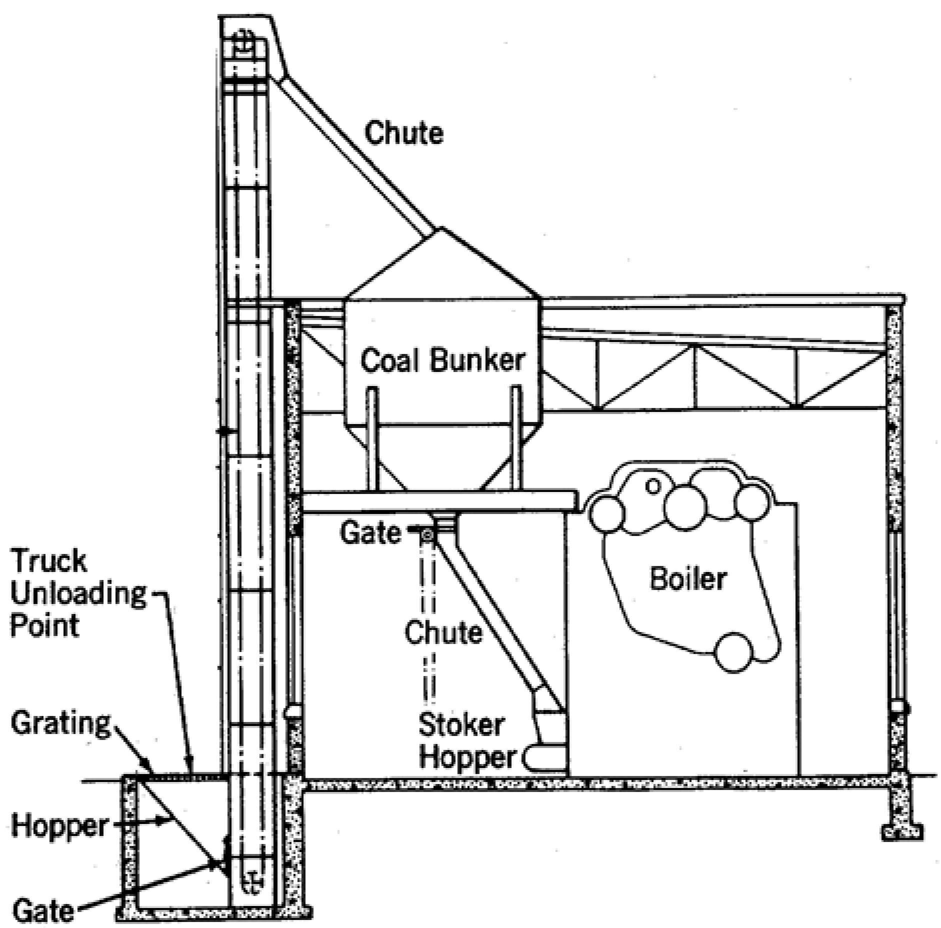


Figure 3 Flow diagram of the fuel conveyance system

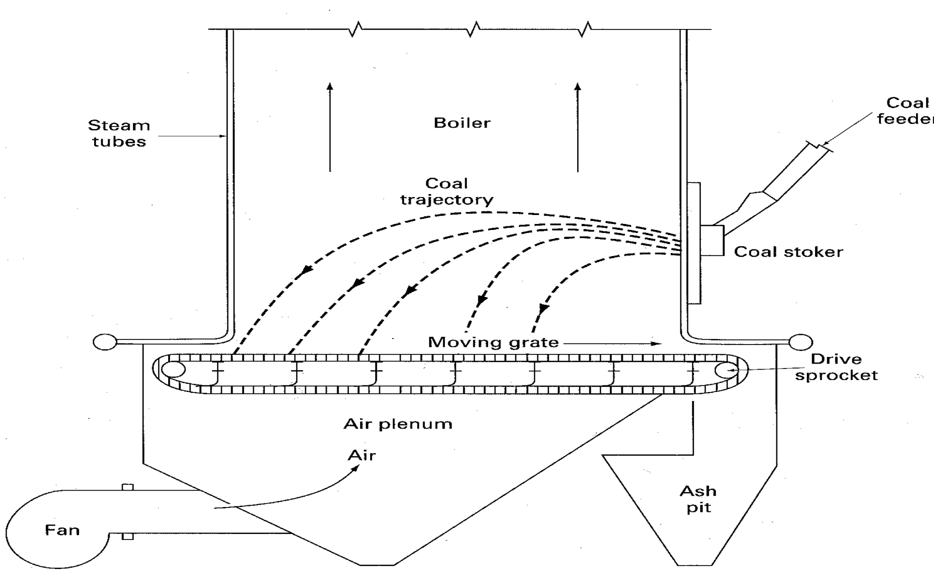


Figure 4 Diagram of the spreader boiler

3.3.2 Test Burns

The demonstration at the NIOSH Boiler Plant was conducted from 10th April to 12th April 2001. In all, a total of 13 tests were performed, of which four were for testing mercury emissions and nine were for testing particulate emissions. Table 2 shows the conditions of all tests conducted in NIOSH Boiler Plant.

On 9th April 2001, the wood/coal blends were made. The blend of construction wood (33% by volume) and coal (67% by volume) was loaded onto one truck; the blend of demolition wood (33% by volume) and coal (67% by volume) was loaded on another one. The blend of construction wood and coal was delivered to the NIOSH boiler plant as soon as the blend was finished.

Table 2. Test Burns at NIOSH

Test No.	Test Type	Fuel	Load (10^3 lb/hr)	Date	Start Time	End Time
N1	Emission	Coal only	17	April 10, 2001	6:00	7:00
N1 (Hg)	Mercury	33% construction wood	17	April 10, 2001	8:00	10:00
N2	Emission			April 10, 2001	10:25	11:50
N3	Emission			April 10, 2001	12:00	13:40
N4	Emission	Coal only	16	April 11, 2001	6:00	7:25
N5	Emission			April 11, 2001	7:40	8:45
N6	Emission			April 11, 2001	9:20	10:25
N7	Mercury			April 11, 2001	10:39	12:39
N8	Emission	33% demolition wood	16	April 12, 2001	5:45	7:00
N9	Emission			April 12, 2001	7:10	8:15
N10	Mercury			April 12, 2001	9:04	11:04
N11	Emission			April 12, 2001	11:34	12:14
N12	Mercury			April 12, 2001	1:05	3:05

On 10th April, four tests were conducted. During three of these tests, 33% construction wood with coal was fired. During the fourth one, only coal was fired. During these four tests Energy System Associates (ESA) monitored the gas emissions or mercury emissions. During each test, data on the flue gas was collected at the stack inlet. During selected tests, particulate sampling was conducted at the economizer exit to determine loading. During other tests elemental, oxidized, and particle-bound mercury were measured also at the economizer outlet. The load on the boiler during the first testing season was about 30%.

On 11th April, the feed was switched back to coal and ESA monitored the gas emissions again from 6:00 a.m. to 12:39 p.m. Another four tests were conducted, three for particulate measurement and one for mercury measurement. The truck-load of blend containing demolition wood was delivered to the NIOSH Boiler Plant for use on the following day.

On 12th April, ESA continued monitoring from 5:45am to 3:05pm, the feed was switched to the blend of demolition wood and coal. A series of five tests was conducted, two tests for mercury measurement, and three for particulate measurement.

Some of the remaining wood was blended at 33-40% by volume wood during the following week, and the boilerplant used it as an alternate fuel until it was depleted. The rest of the remaining wood that had been ground by the J.A.Rutter Company was abandoned in place.

3.3.3 Collection and Calculation of Emission and Particulate Data

Energy System Associates (ESA) monitored emissions during the series of thirteen tests of the demonstrations at the NIOSH boiler plant. The gas analyzers used at both the NIOSH and Bellefield boiler plants included non-dispersive infrared analyzers (NDIR) for CO and CO_2, a chemiluminescence analyzer for NO_x, SO_2 and electrochemical cells for O_2. A sample stream of flue gas was continuously withdrawn from the boiler's stack inlet duct using multiple stainless steel probes, and then conditioned with a sintered metal filter and ice-bath to remove particulates and moisture before the process gas analyzers. A leak check was performed upon the installation of the sampling system. Instruments were calibrated before and after each test. Emissions were recorded electronically every four minutes with a personal computer-based data acquisition system.

During each test, gaseous data was collected at the stack inlet (after the baghouse). During selected tests a particulate sample was collected at the economizer exit (before the baghouse). Testing for elemental, oxidized, and particulate-bound mercury was also conducted at the economizer outlet once per day (once per each fuel). Tests were labeled N1 through N12 with an additional test (N1-Hg).

EPA methods employed in the gaseous sampling include Methods 10, 3A, 6C, and 7E. Particulate sampling was conducted employing Method 17. Mercury sampling was conducted using the Ontario Hydro Method. Figure 5 shows the particulate sampling apparatus.

The flue gas components include O_2, CO, CO_2, NO, H_2O, SO_2 and N_2. During tests all these gases composition could be measured directly except N_2 which is the balance of all other gases. Table 3 provides the flue gas data collected during each test burn.

In order to compare stack emissions and boiler efficiencies from baseline coal operation to those from co-firing with wood chips, a mass balance and an energy balance are needed for each test period. To prepare these two balances, the complete emission data before baghouse is needed. However, the content of the flue gas collected and analyzed after baghouse is somewhat different than that before baghouse, because the gaseous data was collected after the baghouse, and particulate sample was collected before the baghouse. The leak check showed that the percentage of each gas varied from before the baghouse to after the baghouse. Specifically, excess O_2, CO, CO_2, NOx, and SO_2 were collected and analyzed after the baghouse, whereas the moisture, excess O_2 and the volumetric flowrate of flue gas were analyzed before the baghouse. So a series of formulae was used to get the complete information of flue gas before and after the baghouse. All the formulae are listed in the Appendix 1. Table 4 and 5 give the values of the gaseous particulate emissions both before and after the baghouse.

Table 3 The average flue gas data collected during test burns at NIOSH Boiler Plant

	O2 (%)	**CO (ppm)**	**Corrected to 3% O2 CO (ppm)**	**NO (ppm)**	**Corrected to 3% O2 NO (ppm)**	**NO (lb/MMBtu)**	**SO2 (ppm)**	**CO2 (%)**
N1	15.88	182	650.00	86.19	308.19	0.42	140.06	4.28
N1 (Hg)	15.99	195	712.63	90.94	331.75	0.45	137.13	4.21
N2	16.10	168	629.56	83.50	311.56	0.42	120.75	4.16
N3	16.28	178	690.13	79.25	306.63	0.42	115.63	3.83
N4	16.66	220	946.94	77.06	324.06	0.44	109.94	3.64
N5	16.52	199	816.06	76.13	311.56	0.42	119.81	3.74
N6	16.49	209	848.88	75.88	307.56	0.42	120.63	3.80
N7	16.41	173	689.63	75.19	299.75	0.41	117.94	3.84
N8	16.60	290	1228.71	70.52	293.62	0.40	111.57	3.60
N9	16.59	278	1157.92	69.85	290.23	0.39	107.15	3.62
N10	16.45	273	1099.77	69.94	281.23	0.38	107.52	3.68
N11	16.25	273	1053.62	69.57	268.29	0.36	108.62	3.78
N12	16.35	272	1068.91	70.61	277.48	0.38	106.87	3.59

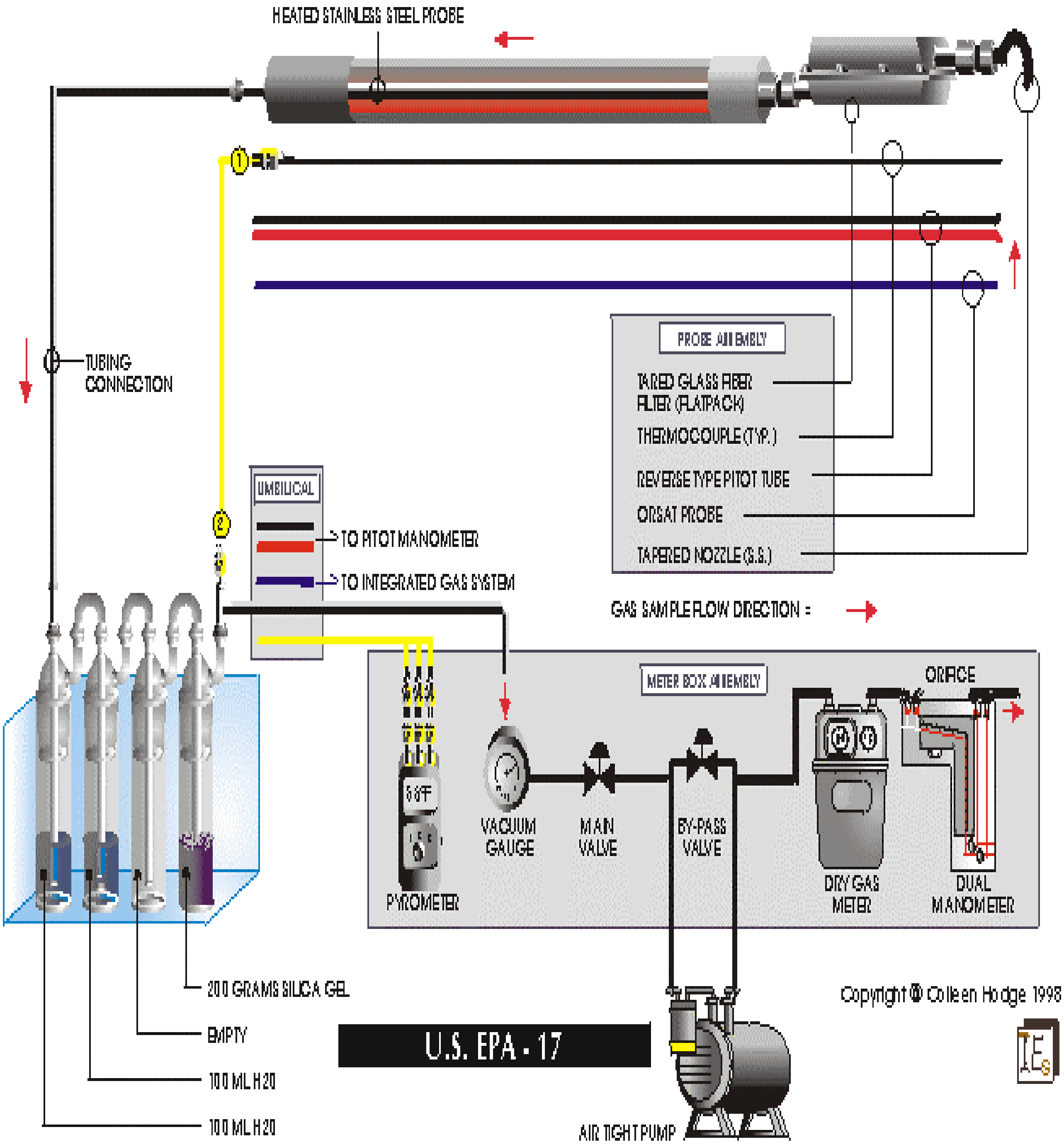


Figure 5 EPA method 17: particulate sampling apparatus[11]

Table 4. Gas and particulate emissions after the baghouse at the NOISH Boiler Plant

After the Baghouse										
	Excess Oxygen (%)	CO@3% Oxygen (ppm)	NO@3% Oxygen (ppm)	NO (lbs/MMBtu)	NO (lbs/hr)	SO2@3% Oxygen (ppm)	SO2 (lbs/hr)	SO2 (lbs/MMBtu)	CO2 (%)	Flow Rate (dscfm)
N1	15.9	650	308	0.420	5.45	501	12.34	0.951	4.3	8843.3
N1 (Hg)	16	713	332			500			4.2	
N2	16.1	630	312	0.400	4.74	451	10.11	0.852	4.2	8381.7
N3	16.3	690	307	0.406	4.54	451	9.51	0.852	3.8	8229.5
N4	16.7	947	324	0.442	4.60	469	9.25	0.889	3.6	8441.8
N5	16.5	816	312	0.422	4.30	488	9.44	0.926	3.7	7897.0
N6	16.5	849	308	0.422	3.47	492	7.69	0.934	3.8	6376.8
N7	16.4	690	300			469			3.8	
N8	16.6	1229	294	0.401	4.35	466	9.54	0.880	3.6	8547.3
N9	16.6	1158	290	0.395	3.79	445	8.06	0.841	3.6	7557.7
N10	16.5	1100	281			439			3.7	
N11	16.3	1054	268			424			3.8	
N12	16.3	1069	277			416			3.6	

Table 5. Gas and particulate emissions before the the baghouse at the NOISH Boiler Plant

Before the baghouse							
	Flow Rate (wacfm)	Flow Rate (dscfm)	Moisture (%)	Excess Oxygen (%)	Particulate Loading (lbs/dscf)	Particulate Loading (lbs/hr)	Particulate Loading (lbs/MMBtu)
N1	13251.7	8843.3	2.6	13.45	8.4704E-05	44.94	2.32
N1(Hg)			4.7	14.1			
N2	13190.0	8381.7	3.8	13.75			
N3	13065.5	8229.5	5.4	14.6	8.958E-05	44.24	2.89
N4	13033.3	8441.8	2.2	15.2			
N5	12341.2	7897.0	4.1	15			
N6	9923.9	6376.8	4	14.9	6.7424E-05	25.80	2.30
N7			4.5	14.5			
N8	13663.7	8547.3	4.4	14.4			
N9	12156.7	7557.7	4.5	14.8	8.8622E-05	40.19	2.95
N10			4.4	14.8			
N11							
N12			3.6	15			

3.3.4 Mass and Energy Balances

Constructing a mass balance and an energy balance is the starting point for all design and performance determinations for boilers and their related components. Based on the calculations of the gaseous and particulate emissions, mass and energy balances were calculated in order to investigate the effect of cofiring on boiler efficiency. Calculation of the mass and energy balances for the two demonstrations gave the following information to the project group and the plant operators: (a) the quantities of the constituents involved in the chemistry of combustion, (b) the quantity of heat released, and (c) the efficiency of the combustion process under actual conditions.

The reactions that occurr during fuel combustion include:

$$C + O_2 = CO_2$$
$$2C + O_2 = 2CO$$
$$2H_2 + O_2 = 2H_2O$$
$$S + O_2 = SO_2$$
$$N_2 + O_2 = 2NO$$
$$CH_4 + 2O_2 = CO_2 + 2H_2O$$
$$2C_2H_2 + 5O_2 = 4CO_2 + 2H_2O$$
$$2C_2H_6 + 7O_2 = 4CO_2 + 6H_2O$$
$$C_2H_4 + 3O_2 = 2CO_2 + 2H_2O$$

The last four reactions occur only when the solid fuel is augmented by co-firing natural gas.

3.3.4.1 <u>Fundamental Laws.</u> The combustion calculations are based on several fundamental laws: [12]

- Conservation of matter

Matter is neither destroyed nor created. There must be an equality between the sum of the weights entering a boiler and the sum leaving. Mass balance calculation was based on this fundamental law.

- Conservation of energy

Energy is neither destroyed nor created. The sum of the energy (potential, kinetic, thermal, chemical and electrical) entering a boiler must equal the sum of energy leaving. This means that the heat released from fuel combustion should equal the sum of the heat absorbed by water, the heat contained in the flue gas, the heat transferred to the stream, the heat contained in the unburned fuel and the heat losses to the environment, i.e.,

$$H_{fuel} = H_{flue\ gas} + H_{unburned\_fuel} + H_{steam} + H_{loss}$$

- The ideal gas law

The volume of an ideal gas is directly proportional to its absolute temperature and inversely proportional to its absolute pressure

- Avogadro's law

Equal volumes of different gases at the same pressure and temperature contain the same number of molecules.

- Dalton's law

The total pressure of a mixture of gases is the sum of the partial pressure which would be exerted by each of the constituents if each gas were to occupy alone the same volume as the mixture.

3.3.4.2 Calculations of Mass and Energy Balance. Mass and energy calculations are undoubtedly important to adjudge the boiler operation.

- Mass balance

For the combustion system, the sum of the weight of fuel (coal or a mixture of coal with wood) and the weight of air entering the boiler should equal the weight of flue gas plus the weight of ash leaving the boiler from the silo, i.e.,

$$W_{fuel} + W_{air} = W_{flue\ gas} + W_{ash}.$$

Figure 6 is a diagram of the mass balance for the boiler operation.

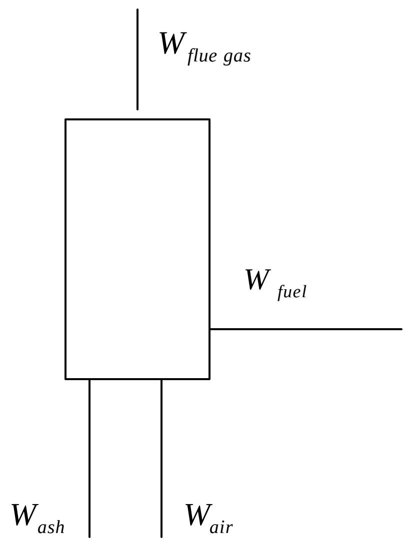


Figure 6 Diagram of the mass balance

Specifically, the constituents contained in the fuel combusted include C, H,N,S and O (on a dry basis) plus H_2O and ash, and those contained in the flue gas are CO_2, SO_2, NO, CO, O_2, N_2 and H_20. By the fundamental laws and reactions described above, we can find the balance between individual species like C, H, S, O, and N. For example, complete combustion of 1lb carbon (C) should produce 44 lb carbon dioxide according to the combustion reaction, and 1 lb carbon (C) needs 32 lb O_2 to combust completely to the product CO_2.

Because the mass flowrate of fuel (whether pure coal or a blend of fuels) that the project team obtained from instruments on-site was not sufficiently accurate to calculate the boiler efficiency, the project team designed a new method to estimate the flowrate of fuel based on using the gaseous and particulate emissions. The calculation utilized: (a) the content of CO_2 in flue gas and the flowrate of flue gas ($W_{flue\ gas}$) to estimate the flowrate of fuel (W_{fuel}), then (b) the fuel analysis and the combustion reactions to estimate the total air flowrate (W_{air}), then (c) the flowrate of ash and the fuel analysis to estimate the mass balance between the mass entering system and that leaving system. A diagram (Figure 7) is shown below to clarify this. This diagram is constructed for a mixture of coal and wood .

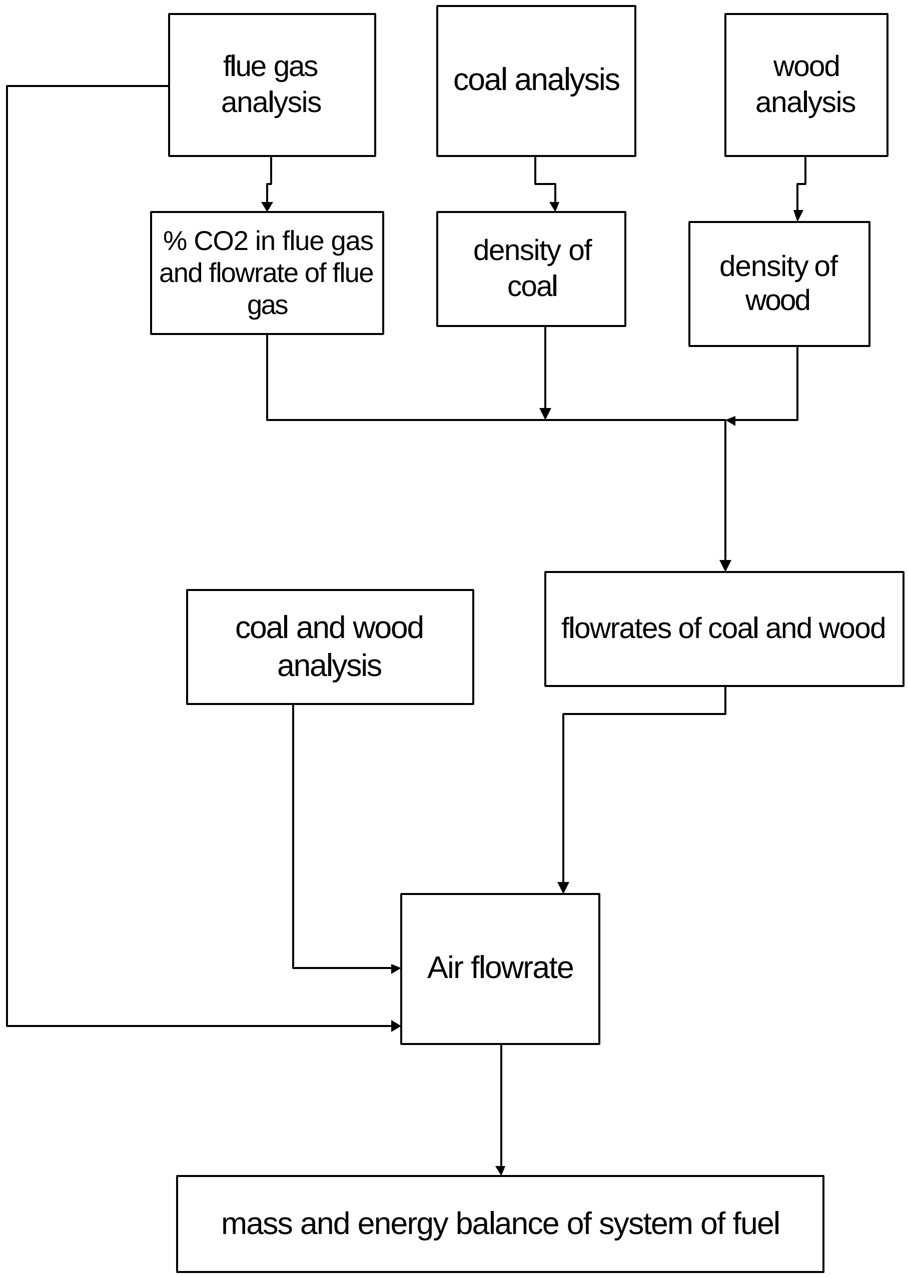


Figure 7 Diagram of the procedure for calculation of flowrates of wood and coal

As an example, Table 6 gives a mass balance calculation for NIOSH Run 1, based on the procedure described in figure 7. In the table, the dark area is the flue gas field, while fuel field is on the left of the table.

Table 6 Mass balance calculation for NIOSH Run 1

Mass Balance of NIOSH Run 1											
Fuel			Flue gas (lb)								Comment:
	Fuel Analysis (lb/lb)	Mixed weight (lb)	O2 Theo Reqd	CO2	CO	O2	N2	H2O	SO2	NO	1.The composition of fuel:Coal 1580.4lb/hr
C to CO2	74.83%	1182.7	3153.8	4320							2.Fuel heat Value:coal 13341 Btu/lb
C to CO	0.29%	4.5	6.0		10.5						
C unburned		0									3.Exit temp of flue gas,t2=330F
H2	5.01%	79.1	633.0					712.1			
O2	8.29%	131.0	-131.0								
N2	0.59%	9.3	4.32				5			8.1	4.Dry -bulb(ambient) temp,t1=48F
S	0.64%	10.1	9.2						18.4		
H2O	2.90%	45.8						45.8			5. Rel humid=43%
ash	7.45%	117.7									
											6. Barometric pressure, in.Hg,B=760
											7 .Sat.Press.H20 at amb temp, in Hg 3.2511
Sum	100.00%	1580.29	3675								
weight of flue gas			40524								8.pressure of H2O in air, A=Rel humid*Sat.Pressure
weight of O2 in flue gas(excess air by lb)			5926			5926					9.Enthalpy of steam(100psi):1187Btu/lb
O2(total), supplied by air=excess air +O2 Ther Reqd			9602								10. Enthalp of feedwater(230F):198Btu/lb
N2(total), supplied by air=29883.6-4.5			29591				29591				
											11.Flowrate of steam(lb):17100 lb/hr
Air(dry)=O2(total)+N2(total)			39193								
H2O in air(lb) = dry air *A/(B-A)			43.8					44			
air(wet)=H2O in air+air(dry)			39237								
Flue gas constituents, total				4320.0	10.5	5926	29596	644.5	18.4	8.1	

- Energy balance

In combustion, chemical energy released from fuel oxidation is changed into the energy in the form of heat, some of which water absorbs to evaporate into steam. However, not all of the heat released from fuel combustion is absorbed by the steam generation equipment. Some of heat is contained in the unburned carbon leaving with the ash, some is brought out by the flue gas, and some is absorbed by the fuel moisture to evaporate. So the calculation of the heat loss is a key step to get the boiler efficiency. Since the heat in the fuel is determined on the basis of ambient temperature, all of the products of combustion must be cooled to the same temperature if all of the heat is to be utilized. High temperature then represents a loss. In general, the energy which is not absorbed by water includes:

(a) the sensible heat in dry flue gas, which is calculated with equation: $\Delta H = w \times Mc_P \times (t_2 - t_1)$, where t_2 and $t_1$are exit temperature of flue gas and ambient temperature respectively. Table 7 shows the relationship of the sensible heat in dry flue gas with flue gas weight and temperature (t_2 and t_1).

Table 7 The sensible heat in dry flue gas

Flue Gas Constituent	N_2	CO_2	H_2O	SO_2	O_2	CO	NO	Sum
Flue Gas Content, W (lb)								
M_{cp}(Btu/lb.F)	0.220	0.25	0.223	0.214	0.451	0.159	0.25	
Exit temperature of flue gas, t_2(F)								
Dry-bulb (ambient) temperature, t_1 (F)								
$H=W\times Mcp\times(t_2-t_1)$ (Btu)								

(b) The sensible heat of the moisture in the air

(c) the sensible heat in the H2O in the fuel

(d) the latent heat of the moisture in the fuel, as shown in table 8.

Table 8 the sensible heat in the moisture in the air and fuel, and the latent heat in the moisture in the fuel

	Resource	Weight (lb)	Mcp (Btu/mole.F)	Sensible Heat	Latent Heat
H_2O	H_2O from Air	W1		$W1\times Mcp\times(t_2 - t_1)$	
	H_2O from combustion of H_2 of fuel	W2		$W2\times Mcp\times(t_2 - t_1)$	$\underline{W2\times1040\times18}$
	H_2O from fuel	W3		$W3\times Mcp\times(t_2 - t_1)$	$\underline{W3\times1040\times18}$

Table 9 shows the energy balance calculation for NIOSH test 1.

Table 9 Energy balance calculation for NIOSH test 1

Energy Balance of NIOSH Run 1								
Flue gas constituents	**CO2**	**CO**	**O2**	**N2**	**H2O**	**SO2**	**NO**	**Total**
Mcp,mean, t2 to t1	0.220	0.25	0.223	0.214	0.451	0.159	8.100	
In dry flue gas=mass each*Mcp*(t2-t1)	2.7E+05	740.25	3.7E+05	2.E+06		8.3E+02	1.9E+04	2.4E+06
in sens heat, H2O in air=weight H2O,M21 *Mcp*(t2-t1)					5570			5570
In sens heat, H2O in fuel=(M4+M9+M10+M11)*Mcp*(t2-t1)					9.6E+04			9.6E+04
in latent heat,H2O in fuel=(M4+M9+M10+M11)*1040					7.9E+05			7.9E+05
Total in wet flue gas								3322247
Due to carbon in refuse =line()*14100								0
Due to unburned CO in flue gas=weight C to CO*9755								43898
Total flue gas losses+unburned combustible=P30+P31+P32								3366145
Heat from fuel combustion=weight of fuel(mixture)* heat content per lb								2.1083E+07
Heat adsorbed by steam								1.6912E+07
Heat loss								8.0455E+05
coefficency of boiler=Heat adsorbed by steam/Heat from fuel combustion								80.22%

3.4. Demonstration in the Bellefield Boiler Plant

3.4.1 Bellefield Boiler Plant

The Bellefield Boiler Plant (BBP) supplies steam for a district heating system that services the majority of the institutional buildings in the Oakland section of Pittsburgh. The plant produces steam with (a) two underfeed multiple-retort stoker boilers, (b) three chain-grate coal-fired stoker boilers and (c) two gas-fired boilers. The cofiring demonstration was conducted in Boiler #1, one of the chain-grate stoker boilers. The Allegheny County Health Department (ACHD) has primacy for air quality assurance at the boiler plant. The plant's Title V air pollution permit limits its SO_2 and particulate emissions. To help limit particulate emissions gas over-fire was added to the boilers many years ago. The boilers are not equipped with any other pollution control device.

The plant produces saturated steam at approximately 175 psig and 375F. It operates 24 hours per day year round. The coal burned at BBP is a near compliance 3/4" x 1/4 " Eastern Kentucky stoker coal that is shipped by barge to the MonValley Transportation Company on the Monongahela River, where it is transferred to 70-ton railcars for transport to BBP. Once a railcar is in the plant, the coal is bottom dumped into a hopper and through a crusher (used to break-up frozen coal) to a 40-ton/hour bucket conveyer/elevator. The conveyer transports the coal across the top of the plant up to a series of five bunkers. Each bunker holds about 500 tons of coal.

Coal for Boiler #1 is unloaded by gravity from the bottom of its bunker through a chute into a non-functioning Stock coal scale. From the scale, the coal passes through a Stock conical non-segregation distributor, which spreads the coal evenly across the entrance to the air-cooled chain grate. Ambient air is used for combustion. Dampers are manually adjusted to distribute the flow of undergrate air. Bed depth and grate speed are adjusted to match the load. Pneumatic-electronic controls are used to manage the boiler. Figure 8 is the flow chart of the BBP.

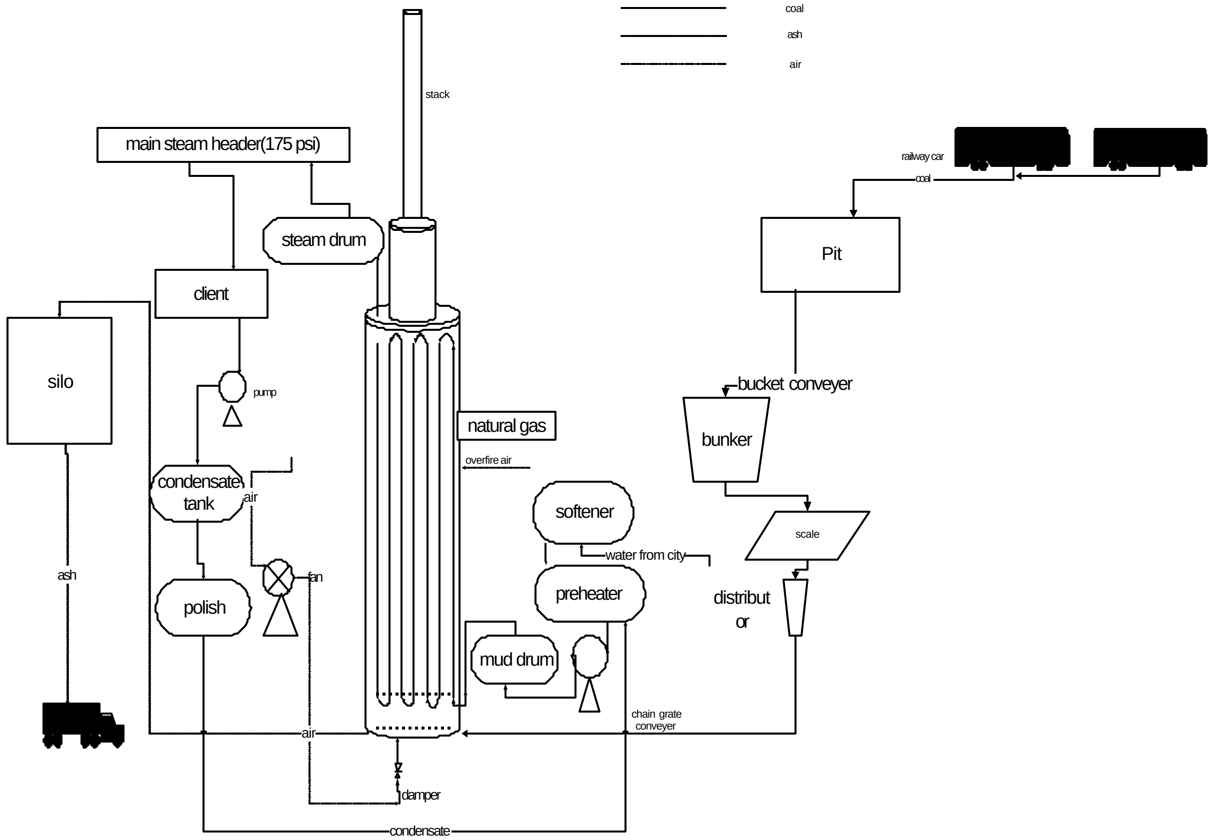


Figure 8 Flow chart of the Bellefield Boiler Plant

3.4.2 Test Burns

Tests in the BBP were conducted in two periods:

- **March 26** ~**March 28**

Three tests were conducted during this period. On March 26 a blend of 80% coal and 20% construction wood by volume, hammermilled by Emery Tree Service, was combusted. On March 27 a 33% blend of construction wood, tub ground by J.A.Rutter was combusted. On March 28, a 40% blend of construction wood, tub ground by J.A. Rutter, was combusted. Unfortunately, ESA wasn't able to monitor the gas and particulate emissions as planned, so the main objectives of these tests were confined to observing the characteristics of biomass/coal flow, the mechanical operation of the boiler and the combustion of the fuel.

More importantly, since (1) the stock coal scale to measure the fuel flowrate was inoperative and (2) otherwise the fuel flowrate to the BBP would have to be back-calculated from steam production (as was necessary for the NIOSH Boiler Plant), which was thought to be less accurate for calculating the mass and energy balances and the boiler efficiency, another activity of project team was to calibrate the feedrate with the rate of travel of the chain grate, so as to be able to estimate the flowrate of the fuel blend during the tests on April 3 and April 4.

Because the fuel flowrate is determined by the speed and the height of gate leading onto the traveling grate, the speed of the chain grate was measured, the height of the gate opening to the of chain grate and the boiler loading were collected and recorded during each test. At the same time the project team weighed one hour's fuel through the feed system by opening the six-inch bypass line (installed specially for sampling), collecting the fuel in buckets, weighing the buckets, and returning the fuel to the distributor. After comparing to the weighed flowrates, the project group found the figure calculated from speed and gate height of the traveling grate didn't exactly indicate the real flowrate of blend fuel, probably because the chain grate looks like a curve not a linear line when it moves if observed from the side. Therefore calculating the volume of fuel simply by multiplying the height of the grate gate with the speed of the chain grate was not accurate enough. Therefore in the calculation of the mass and energy balances, the values calculated from flue gas emissions were still used.

- **April 3~ April 4, 2001**

On April 3, four tests with pure coal were conducted in boiler #1, of which two were conducted at a load of approximately 54 KPPH, and the others at a load of 37 KPPH. ESA monitored the gas and particulate emissions during the four tests. Gaseous data was gathered from the Boiler #1 exit duct, while particulate loading was determined near the base of the stack. Tests were labeled BP2-1 through BP2-4.

On April 4, four tests, labeled BP2-5 through BP2-8, were performed with cofiring of a blend of 40% construction wood, tub ground by J.A Rutter Company. BP2-6 was conducted at a load of 54 KPPH and BP2-7 at 36 KPPH in order to compare the stack emission from baseline coal operation to co-firing wood with coal on the same basis. BP2-5 and BP2-8 were conducted at loads of 63 KPPH and 41KPPH respectively. During these two tests the feed flowrate was varying; therefore these results have not been used for comparisons. Table 10 gives all the tests conducted at BBP during which ESA collected gaseous and particulate emission data.

Table 10 Test burns at BBP

Test	Test Conditions	Test Type	Date	Start Time	End Time	Boiler Load KPPH
BP2-1	Pure coal	Particulate	April 3, 2001	10:25	11:47	54.3
BP2-2		Particulate	April 3, 2001	12:15	13:27	53.4
BP2-3		Particulate	April 3, 2001	16:07	17:26	36.4
BP2-4		Particulate	April 3, 2001	17:48	19:05	36.6
BP2-5	40% construction wood	Particulate	April 4, 2001	12:12	13:26	63.3
BP2-6		Particulate	April 4, 2001	13:55	15:12	54
BP2-7		Particulate	April 4, 2001	16:32	17:43	36.9
BP2-8		Particulate	April 4, 2001	18:05	19:30	41.3

3.4.3 Gas and Particulate Emission Data Collection and calculation

Table 11 gives the average emission and particulate data collected during each test burn in Bellefield boiler plant. There are totally 8 tests, BP2-1, BP2-2, BP2-3 and BP2-4 were tests with coal only, while BP2-5, BP2-6, BP2-7 and BP2-8 were tests with blend fuel

Table 11 The average gas and particulate emission data collected during test burns in BBP

	O2 (%)	CO (ppm)	Corrected to 3% O2 CO (ppm)	NO (ppm)	Corrected to 3% O2 NO (ppm)	SO2 (ppm)	Corrected to 3% O2 SO2 (ppm)	CO2 (%)
BP2-1	10.21	25.65	43.00	182.20	305.25	300.55	503.28	8.56
BP2-2	10.37	24.83	42.00	187.11	317.56	300.55	528.98	8.44
BP2-3	13.16	74.42	172.58	120.84	280.00	244.74	565.85	6.26
BP2-4	13.24	72.16	168.37	120.47	280.89	239.00	558.27	6.32
BP2-5	8.98	72.16	44.95	241.42	362.58	306.42	460.31	10.13
BP2-6	10.58	29.00	50.28	207.56	359.89	249.50	432.66	8.56
BP2-7	13.00	59.00	134.41	133.82	303.88	199.94	455.06	6.57
BP2-8	12.25	36.50	75.45	156.85	324.40	199.95	413.91	7.34

Table 12 and 13 shows the gas and particulate emissions in the cuct and the stack. Similar to flue gas collection and calculation, those data collected from the stack and the duct are somewhat different from each other because the leakage of ambient air changes the percentages of components from the duct to the stack. Specifically, excess O_2, CO, CO_2, NOx, and SO_2 were collected and analyzed in the duct, whereas the moisture, excess O_2 and the volumetric flowrate of flue gas were analyzed in the stack. The same series of formulae used in NIOSH demonstration calculation were used to obtain the complete information on the flue gas in the duct and in the stack. All the formulae are listed in Appendix 1.

Table 12 Gas and particulate emissions in the Duct of Boiler #1 in the BBP

Test No.	Duct Data									
	Excess Oxygen (%)	CO@3% Oxygen (ppm)	NO@3% Oxygen (ppm)	NOx (lbs/hr)	NOx (lbs/MMBtu)	SO2@3% Oxygen (ppm)	SO2 (lbs/hr)	SO2 (lbs/MMBtu)	CO2 (%)	Flow Rate (dscfm)
BP2-1	10.2	43	305	52.43	0.399	503	120.65	0.919	8.6	40217.96355
BP2-2	10.4	42	318	47.12	0.418	529	109.03	0.968	8.4	35175.64682
BP2-3	13.2	173	280	42.04	0.369	566	118.43	1.040	6.3	48502.22195
BP2-4	13.2	168	281	35.57	0.366	558	98.56	1.014	6.3	41379.8414
BP2-5	9.0	45	363	49.82	0.474	460	88.02	0.837	10.1	28861.4217
BP2-6	10.6	50	360	48.03	0.472	433	80.32	0.790	8.6	32236.20132
BP2-7	13.0	134	304	24.58	0.397	455	51.04	0.824	6.6	25605.17362
BP2-8	12.3	75	324	28.60	0.427	414	50.69	0.757	7.3	25428.35657

Table 13 Gas and particulate emissions in the Duct of Boiler #1 in the BBP

Test No.	Stack Data							Filter No.
	Flow Rate (wacfm)	Flow Rate (dscfm)	Moisture (%)	Excess Oxygen (%)	Particulate Loading (lbs/dscf)	Particulate Loading (lbs/hr)	Particulate Loading (lbs/MMBtu)	
BP2-1	97063.2	57377.6	3.9	13.4	1.73271E-05	59.65	0.454	2
BP2-2	93024	54315.3	5.1	14.1	1.66544E-05	54.28	0.482	3
BP2-3	100490.4	63299.5	1.9	15	1.1149E-05	42.34	0.372	4
BP2-4	89964	55899.1	3.6	15.2	1.18917E-05	39.88	0.410	5
BP2-5	74235.6	44032.2	3.5	13.1	2.04459E-05	54.02	0.513	6
BP2-6	74235.6	43688.5	4.9	13.3	1.80078E-05	47.20	0.464	7
BP2-7	64749.6	39662.9	3.9	15.8	1.36809E-05	32.56	0.525	8
BP2-8	64688.4	39760.7	3.3	15.4	1.43608E-05	34.26	0.511	41

3.4.4 Mass and Energy Balances

During the tests on April 3 and April 4, the project team wasn't able to weigh one hour's fuel through the feed system by use of the six-inch bypass line (installed specially for sampling) as it did on March 26 and March 27. Therefore the flowrates of the 40% blend were calculated from the flue gas compositions as performed in NIOSH demonstration.

A significant difference from the tests conducted in NIOSH Boiler Plant was that, natural gas was combusted together with pure coal or blend fuel (wood/coal) in the BBP. The boiler plant has an instrument for volumetric flowrate of natural gas.

4. 0 ACCOMPLISHMENTS OF THE DEMOSTRATIONS

4.1. Fuel Preparation

Based on previous experience of the two demonstrations conducted earlier by the project team at the Pittsburgh Brewing Company and the NIOSH Boiler Plant, the critical bottleneck for handling fuel blends of wood and coal occurred at the receiving grill and feed pit. Several factors appear to be responsible for this limitation: (1) percent wood in the blend, (2) percent moisture, (3) word shape, which varies with the method of processing, and (4) fines, which varies with the method of processing and blending. As one example, at the Pittsburgh Brewing Company, the project team found that, using a blend with too many fines, accumulations of fines would build up gradually in the day bin. When the accumulation slumped, it would cause plugging in the conveyance system and need extra labor to keep it moving, especially when the fuel was soaking wet.

Wood content

- **BBP**

At BBP, when the wood volume in the blend was 40%, the plant operators had considerable difficulty starting its removal from the bottom of the rail car, and occasionally they had to encourage it to slump from the sides of the feed pit to the 30-inch pipe at the bottom of the pit. During most of demonstration this blend flowed through lines leading from the bunker to the boiler without incident, but intermittently the "no flow" alarm would sound. Often the alarm would stop after a minute or so without intervention by the operators, but on some occasions the operators would have to pound the feed pipe to move the blend along. When the wood volume in the blend was 20%, the blend fed well from the railcar to the bunker, and moved smoothly in the rest of conveyance system without extra encouragement. However the blend fuel with 33% wood, while feeding well from railcar to the bunker, caused the “no flow” alarm to sound occasionally.

- **NIOSH**

In contrast to the experience of the previous demonstration conducted in the NIOSH boilerplant when a wood content more than approximately 33% in the blend caused the fuel blend to bridge the openings in the grill and to need frequent intervention to maintain flow, in this demonstration using a blend having the content of hammermilled construction and demolition wood of 33%, the blend fuel easily passed through the receiving grill and moved along the chute/pipe to the spreader system without the need for any intervention.

Fines and moisture

- **BBP**

The wood used for demonstration at BBP was either construction wood or a mixture of pellets and construction wood. Most of this wood was a mixture processed by the tub grinder of JARC, and a small part was processed by the hammermill of ETS. The tub grinding of wood by JARC produced more fines than the hammermilling of wood by ETS. In addition, when preparing the fuel for the demonstration at BBP, as mentioned in the section 2.3, the overnight temperature drop below -12°C caused both the coal and wood piles to freeze, so when they were layered on the ground for blending, the front-loader had to drive over the wood and coal several times to break up the frozen lumps. Doing so produced many fines. What's more, because of the existence of much moisture (snow/ice) in the mixture, some fines clung together during the process of delivery to the plant and in the plant's fuel conveyance system. Some lumps were also formed subsequent to delivery. These lumps had difficulty in getting through the receiving grill and couldn't moved smoothly in the fuel conveyance system either, especially at the higher wood contents in the 33% and 40% wood/coal blends.

- **NIOSH**

Some of the wood used for the demonstration at NIOSH was construction wood and some was demolition wood, of which the most flowable was that processed by hammermilling of Emery Tree Service. It had been hoped that the wood supplied by J.A.Rutter Co. would be more flowable because of a further wood modification made to the tub grinder. The fines contained in the JARC blends were less than those in the blend combusted in the BBP, but flowablity was not much improved. In addition, the coal pile and wood pile hadn't been covered by snow, so there was less moisture too.

Processing and blending

- **BBP**

Wood used in the Bellefield Boiler Plant was a mixture of pellets and the construction wood the J.A. Rutter Co. collected from condominium construction site, and processed by the modified tub grinder into wood pieces, most of which were cubic with ratio 6:1:1of length to width to depth; however a few pieces were up to six inches long and contained a high fraction of sawdust-like material (<1/4 inch). The fines caused a problem to keep the fuel blend moving smoothly. Therefore, the method with the modified tub grinder to process construction wood is not desirable.

Wood used in the BBP was blended with coal on the ground using a front-loader with a single bucket and a FECON blender with a 7.5m3 hopper. In the process of being delivered to the boiler plant, dumped into the receiving hopper, raised and dumped into bunker, transferred through the chute and into the boiler, the blend fuel was mixed continuously. From the project team's observation, the mixing was acceptable. But as mentioned in section 3.2.3, because of the snow and ice covering on the wood and coal storage piles, the frozen lumps had to be broke up with front-loader driving over the blend. This produced more undesirable fines which increased the difficulty of the blend's flowing in the conveyance system.

- **NIOSH**

Both construction wood and demolition wood were used in the NIOSH Boiler Plant. Construction wood was processed in the same way as at the BBP. A part of the demolition wood was processed by the modified tub grinder and a material with a smaller top size and many more fines were produced. The rest of demolition wood was processed by the hammermill of ETS. The material produced in this method contained fewer fines and had a more consistent aspect ratio than was produced from the construction. Therefore, the method with the hammermill to process demolition wood is acceptable.

Wood used in the NIOSH tests was blended with coal on the ground using a single front-end loader. Similar to the situation in the BBP tests, in the processing of blend delivery the mixing was enhanced, and the mixing result is very acceptable, as shown in Picture 9.

The project team concludes from both demonstrations that: **A**. the wood processed by the tub grinder contains more fines than that processed by the hammermill; **B**. processed demolition wood contains less fines than processed construction wood.

4.2. Combustion

- **NIOSH**

Once fed to the grate, properly prepared wood/coal mixtures of both construction wood and demonstration wood met the demonstration's goal for combustion characteristics. There were no occurrences of flame propagating back into the fresh fuel in the spreader, or discharge of still-burning ash particles into the ash pit or out of the boiler during any test. The load requirement was also met during the tests. Boiler operations were relatively smooth during all the demonstration tests. However, since compared to coal, wood has a high volatile content, a low heat content and a low density, a higher rate of feed is needed. This wouldn't cause difficulty when the load is low, but it is not easy when the load is high.

- **BBP**

The fuel blends with 20% and 33% wood by volume combusted well. There was no difference in the fire in the boiler from that observed with coal alone. Also, there were no occurrences of flame propagating back into the fresh fuel across the gate, or discharge of still-burning ash particles into the ash pit or out of the boiler. The load requirement was met. However, for the combustion of the fuel blend with 40% wood by volume, there was a thin tongue of apparently unburned material extending along the left side of the grate, which could be allowing hot, unburned material to drop into the ash pit, and there was a lot of fine ash floating around as well. In addition, more slag was viewed on the front wall and layer, harden pieces of slay were found in the ash pit.

4.3 Gaseous Emissions

- **NIOSH**

Table 14 shows the average flue gas and particulate emissions and the corresponding operational parameters during each test burn in NIOSH. Run N1 used coal only with load of 17.1×10^3 lb/hr; Run N (2+3) is the average of Runs N2 and N3, in which construction wood and coal were cofired with a boiler load of 16.9×10^3 lb/hr; Run N (4+5) is the average of Runs N4 and N5, in which coal only was fired with a load of 15.9×10^3 lb/hr; and Run N (8+9) is the average of Runs N8 and N9, in which demolition wood and coal were cofired with load of 16.1×10^3 lb/hr.

Table 14 Operational parameters and flue gas emissions of NIOSH tests

Operational Parameters and Flue Gas Emissions					
	TEST	N1	N (2+3)	N (4+5+6)	N (8+9)
	TEST DATE	Apr.10, 2001	Apr.10, 2001	Apr.11, 2001	Apr.12, 2001
	BOILER	Boiler #1	Boiler #1	Boiler #1	Boiler #1
	CONTENT OF FUEL	Pure coal	33% construction wood	Pure coal	33% demolition wood
	LOAD (10^3lb/hr)	17.1	16.9	15.9	16.1
OPERATION PARAMETER	Before-baghouse temperature (F)	330	330	325	335
	Dry-bulb (ambient) temperature (F)	48	48	50	52
	Relative humidity of air (%)	43	43	42	41
	Flowrate of steam (10^3 lb/hr)	17.1	16.9	15.9	16.1
	Temperature of feedwater (F)	230	230	230	230
	Pressure of steam (psig)	100	99	99	99
EMISSION	CO@3% Oxygen (ppm)	650	660	871	1193.5
	NOx (lbs/MMBTU) (ppm)	0.42	0.403	0.429	0.398
	NOx@ 3% Oxygen (ppm)	308	309	315	292
	SO2@3%Oxygen	501	451	483	455
PARTICULATE	Particulate Loading (lbs/dscf)	8.47×10^{-7}	8.96×10^{-7}	6.74×10^{-7}	8.86×10^{-7}
	Particulate Loading (lbs/MMBTU)	2.32	2.89	2.3	2.95

Table 15 shows the changes of both gas and particulate emissions when switching from the combustion of pure coal and the cofiring of wood and coal. We used the average value for the tests of N2 and N3, N4,N5, and N6, N8 and N9, because they were the tests with same kind of input fuel.

Table 15 Emissions' changes from the combustion of pure coal and cofiring wood/coal in NIOSH tests

TEST	CONTENT OF FUEL	LOAD (10^3lb/hr)	CO @3% Oxygen (ppm)	NOx (lbs/MMBtu)	NOx @ 3% Oxygen (ppm)	SOx (lbs/MMBtu)	SOx @3% Oxygen (ppm)	Particulate (lbs/MMBtu)
N1	pure coal	17.1	650	0.42	308	0.951	501	2.32
N (2+3)	coal:wood=2:1	16.9	660	0.403	309	0.852	451	2.89
Change of emissions			*1.54%*	*-4.05%*	*0.32%*	*-10.41%*	*-9.98%*	*19.72%*
N(4+5+6)	pure coal	15.9	871	0.429	315	0.916	483	2.3
N(8+9)	coal:wood=2:1	16.1	1193.5	0.398	292	0.861	455	2.95
Change of emissions			*37.03%*	*-7.23%*	*-7.30%*	*-6.00%*	*-5.80%*	*22.03%*

From the above two tables, it may be concluded that cofiring lowered emissions for SO_2 and NOx, with average levels of 451-455 ppm SO_2 and 292-309 ppm NOx (corrected to 3% dry O_2) that correspond to about 0.852-0.861 lb SO_2/MMBtu and 0.398-0.403 lb NOx/MMBtu. These results for SO2 were consistent with the low sulfur of the construction wood and demolition wood as compared to the pure stoker coal. Because it is not only produced from the oxidation of the nitrogen contained in the fuel (fuel–NOx) but also from the nitrogen in the combustion air (thermal–NOx), NOx formation is influenced by heat release rate, furnace temperature and excess O_2. In this demonstration, it appears that conditions of operation and the equipment at the NIOSH boiler plant enable NOx to be reduced when cofiring wood with coal.

- **BBP**

Table 16 shows the average flue gas and particulate emissions and the corresponding operational parameters during each test burn in BBP. Run BP2- (1+2) is the average of Runs BP2-1 and BP2-2, in which coal only was fired with a boiler load of 54×103 lb/hr; Run BP2-6 in which a blend of 33% construction wood and coal was cofired with a boiler load of 54×103 lb/hr; BP2- (3+4) is the average of Runs BP2-3 and BP2-4, in which coal only was fired, operated with a boiler load of 37×103 lb/hr; and Run

BP2-7, in which a blend of 33% construction wood and coal was fired, operated with a boiler load of 34×103 lb/hr.

Table 16 Operational parameters and flue gas and particulate emissions of BBP tests

	TEST	**BP2- (1+2)**	**BP2-6**	**BP2- (3+4)**	**BP2-7**
	TEST DATE	Apr.3, 2001	Apr.4, 2001	Apr.3, 2001	Apr.4, 2001
	BOILER	Boiler #1	Boiler #1	Boiler #1	Boiler #1
	CONTENT OF FUEL	Pure coal	40% wood	Pure coal	40% wood
OPERATION PARAMETER	Exit temperature of flue gas (F)	609.15	615.2	557.05	561.3
	Ambient temperature, t1(F)	46	50	46	50
	Relative humidity of air (%)	35	35	35	35
	Flowrate of water (10^3 lb/hr)	56.35	55.9	39.75	39.8
	Flowrate of steam (10^3 lb/hr)	53.38	54	36.5	36.9
	Flowrate of natural gas	17.7	18.7	11.8	11.3
	Temperature of feedwater (F)	235	235	235	235
	Pressure of steam (psig)	175	175	175	175
EMISSION	CO@3% Oxygen (ppm)	42.5	50.28	170.5	134
	NOx (lbs/MMBTU)	0.409	0.472	0.368	0.397
	NOx@ 3% Oxygen (ppm)	311.4	359.89	280.4	304
	SOx (lbs/MMBTU)	0.943	0.79	1.027	0.824
	SO2@3%Oxygen (ppm)	516.13	432.66	562.1	455
PARTICULATE	Particulate Loading (lbs/dscf)	1.70×10^{-5}	1.80×10^{-5}	1.15×10^{-5}	1.37×10^{-5}
	Particulate Loading (lbs/MMBTU)	0.468	0.464	0.391	0.525

Table 17 shows the changes in both gas and particulate emission when switching from the combustion of pure coal to the cofiring wood and coal.

Table 17 Emissions' changes from the combustion of pure coal and cofiring wood/coal in BBP tests

TEST	CONTENT OF FUEL	LOAD (10^3lb/hr)	CO @3% Oxygen (ppm)	NOx (lbs/MMBtu)	NOx @ 3% Oxygen (ppm)	SOx (lbs/MMBtu)	SOx @3% Oxygen (ppm)	Particulate (lbs/MMBtu)
BP2- (1+2)	pure coal	54	42.5	0.409	311.4	0.943	516.13	0.468
BP2-6	40% wood	54	50.28	0.472	359.89	0.79	432.66	0.464
Change of emissions			*18.31%*	*15.40%*	*15.57%*	*-16.22%*	*-16.17%*	*-0.85%*
BP2- (3+4)	pure coal	37	170.5	0.368	280.4	1.027	562.1	0.391
BP2-7	40% wood	37	134	0.397	304	0.824	455	0.525
Change of emissions			*-21.4%*	*7.88%*	*8.42%*	*-19.77%*	*-19.05%*	*34.27%*

From the above two tables, it may be concluded that the emission of SOx from cofiring was lower than from combusting pure coal, with average levels of 432-455 ppm (corrected to 3% dry O_2). This corresponds to about 0.464-0.525 lb SO_2/MMBtu. This result is consistent with the low sulfur content of construction wood as compared to pure stoker coal. However NOx emission was increased, rather than decreased as expected. The project team thinks that the big lumps, which were formed due to too much moisture and too many fines, were responsible for this unexpected result. The big lumps were more solid than other particles, so it prevented the cooling air, which came from the bottom of the boiler, from penetrating and approaching the surface of the big lumps, thus the surface temperature of the big lumps is higher than its nearby environment, therefore more thermal NO could be produced due to the existence of these "hot-spots". Unfortunately because there lacked instruments to measure the inside temperature of the boiler, the project team is not able to give the explanation in detail of how the temperature profile resulted in the increase of NOx.

4.4 Mass Balance and Energy Balance

- **NIOSH**

Table 18 shows the comparative results of the mass balances of the NIOSH tests

Table 18 Comparative results of mass balances of NIOSH tests

Test	Fuel content	Load (10^3lb/hr)	Fuel (lb)	Wet Air (lb)	Flue gas (lb)	Ash (lb)	Error	Boiler efficiency
NI	pure coal	17	1580	39237	40524	118	0.4%	80.22%
N (2+3)	construction wood(33%)/coal	17	1934	36214	37963	185	0.0%	77.64%
N (4+5+6)	pure coal	16	1458	33343	34666	109	0.1%	80.83%
N (8+9)	demolition wood (33%)/coal	16	1680	35182	36825	143	0.3%	78.66%

❖ Runs N1 and N (2+3)

During the tests of N1 and N (2+3), the same amount of steam was produced (17,000 lb/hr). From table 18, it can be seen that the amount of blend fuel required is more than that of pure coal. This is consistent with the fact of the density of wood is about half that of coal and the heating value of wood is far less than that of pure coal.

From table 5, table 12 and table 13, we can see that the excess O_2 in each test both at NIOSH and BBP was very high. The reason is that all the loads of both boilers during the demonstrations were lower compared to their maximum capacity. Under this condition more cool air must be used to prevent ash from melting due to the high temperatures inside the boilers.

Since more moisture was contained in the blend fed during Run N (2+3) compared to that in the pure coal fuel fed during Run N1, it absorbed more of the heat released from during combustion, thus reducing the boiler efficiency a little.

❖ Runs N (4+5+6) and N (8+9)

Just as in Runs N1 and N (2+3), the amount of blend fuel used at the same steam make is also more than that of pure coal.

Also, just as in Runs N1 and N (2+3), the boiler efficiency was reduced a little bit when changing from pure coal to blend fuel due to a higher moisture content.

All of the mass balances back-calculated from the flue gas analysis were much more accurate. with the maximum error being 0.4%. This proved that the method of back-calculation of the flowrate of the fuel from flue gas is acceptable. The detailed calculation tables of mass balances are listed in Appendix 4,5,6 and 7.

- **BBP**

Table 19 shows the comparative results of the mass balances of the BBP tests

Table 19 Comparative results of mass balance of BBP tests

Test	Fuel content	Load (10^3lb/hr)	Fuel (lb)	Wet Air (lb)	Flue gas (lb)	Ash (lb)	Error	Boiler efficiency
BP2-(1+2)	pure coal	54	5071	71033	79006	352	3.1%	62.1%
BP2-6	construction wood(40%)/coal	54	5753	63257	70295	391	1.1%	60.32%
BP2-(3+4)	pure coal	37	3608	33343	90144	250	1.4%	60.04%
BP2-7	Construction wood (40%)/coal	37	4136	52255	57077	281	0.3%	59.55%

❖ Runs BP2- (1+2) and BP2-6

During Runs BP2- (1+2) and BP2-6, same amount of steam was produced (54,000 lb/hr). From table 20, it can be seen that the amount of blend fuel required is more than that of pure coal. This is consistent with the fact of the density of wood is about half that of coal and the heating value of wood is far less than that of pure coal. Since more moisture was contained in the blend fed during Run BP2- 6 compared to that in the pure coal fed during Run BP2- (1+2), it absorbed more of the heat released during combustion, thus reducing the boiler efficiency a little.

❖ Runs BP2- (3+4) and BP2-7

Just as in Runs BP2- (1+2) and BP2-6, the amount of blend fuel used at the same stream make is also more than that of pure coal.

Also, just as in Runs BP2- (1+2) and BP2-7, the boiler efficiency was reduced a little when changing from pure coal to blend fuel due to a higher moisture content.

All of the mass balances back-calculated from the flue gas analysis seemed accurate, with maximum error being 3.1%. This also proved that the method of back-calculation of the flowrate of fuel from the flue gas is acceptable. The detail calculation tables of mass balances are listed in Appendix 8,9 10 and 11.

Compared with boiler efficiencies of NIOSH, the project team found the boiler efficiency of the BBP to be far lower. This is because there is an economizer installed in the boiler system at NIOSH whereas none is in the BBP system.

5.0 CONCLUSIONS

- **NIOSH**

The wood/coal fuel blend using wood processed by Emery Tree Service is acceptable for use on a commercial basis. The appropriate characteristics of the wood to be sought are:

- Type of wood: Demolition wood (preferred) and construction wood
- Size of wood: Top size 3”
- Moisture: ≤ 20%
- Wood collectors: J.A.Rutter Company and/or Emery Tree Service from contractors and industrial plants
- Wood processing: Emery Tree Service
- Blend ratios: 20%~40% by volume
- Blending: on the ground
- Boiler plant modification: None

In general, the next steps in the NIOSH project include: determining acceptable sources of wood and locating required quantities; developing business plan for commercialization of wood/coal cofiring at NIOSH; and acquiring the air permit for long-term cofiring of wood from ACHD.

- **BBP**

The wood/coal fuel blend used in this demonstration can’t be used on a commercial basis for several reasons. First, it caused problems in the conveyance system. Most of this difficulty was due to excessive fines which were produced during processing and blending at J.A.Rutter Co. and MVTC. Second, a wood/coal fuel blend in general can’t be used on a commercial basis at BBP because of the change in the nature of the fly ash emitted from the stack. Third, the fines caused excessive slag buildup on the front wall of the boiler. To commercialize the use of a blend of clean waste wood and coal in the BBP, the project team must seek an improved wood/coal fuel blend, and seek funding to install a baghouse for the BBP.

6. 0 COMMERCIALIZATION

6.1 Regulatory

Applications for permit modifications should be filed (1) by the wood processors with the office of solid waste of the Pennsylvania Department of Environmental Resources (PADEP) to allow them to recycle demolition debris, and (2) by the boilerplants with the office of air quality of the Allegheny County Health Department (ACHD) to allow them to use a wood/coal blend as fuel. Following receipt of temporary permit modifications, compliance testing must be accomplished prior to issuance of permanent permits. The Biomass/Coal Cofiring Group has met with the PADEP and the ACHD to initiate discussions about this program.

6.2 Clean Urban Waste Wood Providers and Processors

Meetings should be held with urban redevelopment agencies of the City of Pittsburgh and of Allegheny County to ascertain their interest in facilitating the provision of clean urban waste wood from their redevelopment projects for this program. Further discussions likely will be required with their demolition contractors.

Meetings should be held with Emery Tree Service and J. A. Rutter Company to detail the specifications and requirements for wood collection, grinding, sizing, fines, storing, delivery schedules, etc., that were suggested by the recent tests at the BBP and the boilerplant at NIOSH. After specifications and requirements are reviewed, it should be determined if the wood providers can and will offer wood for this program. Provision and size of tipping fees will be an important element of these discussions.

6.3 Broker/Blender

Meetings should be held with the coal brokers for the boiler plants, for example, UnionVale Coal Company for NIOSH and Consol for BPP, to seek their participation in the program. Co-ordination and equipment for blending would then be required at Three Rivers and/or Mon Valley Terminals. It may be more economical and practical to have blending at just one terminal for the wood/coal blend. This will be determined after further discussions.

6.4 Transportation

The only change from current operations would be transporting the collected waste wood from demolition sites to the wood processors and the ground wood from the wood processors to the wood/coal-blending site(s). This addition to the procedure should be discussed with the wood providers, the wood processors and the coal brokers.

6.5 Boiler Plants

A meeting should be held with the boiler plant management about:

-Permit modifications

-Existing coal contracts

-Optimal percent wood/coal blend

-Timing of deliveries

-Storage of wood/coal blend

-Fossil carbon credits

6.6 Economic Considerations

The following costs are approximate and subject to change:

Current coal cost…………………..$50/ton Delivered to Terminal

Processed wood cost……………...$15/ton Delivered to Terminal

Heating value of coal……………..13202 Btu/lb (2.6×10^{7} Btu/ton).

Heating value of wood…………… 6,300 Btu/lb (1.26×10^{7} Btu/ton)

Pounds per ton……………………..2,000 lb

Tons of coal in one ton of blend…….0.778 tons of coal

Tons of wood in one ton of blend…..0.222 tons of wood

Cost of wood/coal blend at terminal……..$48.15

(per 1.14 ton, giving the same Btu content as one ton of coal)

Savings using wood/coal blend…………… $1.85/28*E6 Btu

(Note that a portion of this savings will have to be applied to the transportation of the additional 14% tonnage to the boilerplant.)

APPENDIX

APPENDIX 1

Formula

1. Sample volume and isokinetics

a. Sample gas volume, dscf

$$V_{mstd} = 0.03342 V_m [P_{bar} + (H / 13.6)](T_{ref} / T_m)(Y)$$

b. Water vapor volume,scf

$$V_{wstd} = 0.0472 V_{lc} (T_{ref} / 528)$$

c. Moisture content, nondimensional

$$B_{wo} = V_{wstd} / (V_{mstd} + V_{wstd})$$

d. Stack gas molecular weight, lb/lb mole

$$MW_{dry} = 0.44(\%CO_2) + 0.32(\%O_2) + 0.28(\%N_2)$$

e. Absolute stack pressure, iwg

$$P_s = (P_{bar} \times 13.6) + P_{sg}$$

f. Stack velocity, ft/sec

$$V_s = 2.90 C_p (\sqrt{\Delta P})_{avg} \sqrt{T_{s,avg}} \sqrt{\frac{(29.92)(28.95)}{P_s MW_{wet}}}$$

g. Actual stack gas flow rate, wacfm

$$Q = (V_s)(A_s)(60)$$

h. Standard stack gas flow rate, dscfm

$$Q_{sd} = Q(1 - B_{wo})(T_{ref} / T_s)(P_s / 29.92)$$

i. Percent isokinetics

$$I = \frac{17.32 \times T_s (V_{mstd})}{(1-B_{wo}) q \times V_s \times P_s \times D_n{}^2} \times \frac{528}{T_{ref}}$$

2. Gaseous Emissions, lb/hr

$$M = ppm \times 10^{-6} \frac{MW_i \; lb / lb \quad mole}{SV} \times Q_{sd} \times 60 \text{ min}/ \; hr$$

Where SV=specific molar volume of an ideal gas:

385.3 ft3/lb mole for T_{ref}=5280R

379.5 ft3/lb mole for T_{ref}=5200R

3. Gaseous Emissions, lb/hr

$$M = [ppm] \times 10^{-6} \times \frac{MW_i}{SV} \times F \times \frac{20.9}{(20.9 - excess \quad O_2)}$$

Nomenclature:

A_s	Stack area, ft^2
B_{wo}	Flue gas moisture content
$C_{12\%CO_2}$	Particulate grain loading, gr/dsc corrected to 12% CO_2
C	Particulate grain loading, gr/dscf
C_p	Pitot calibration factor, dimensionless
D_n	Nozzle diameter,inches
F	Fuel F factor, dscf/10^6 Btu at 0% O_2
H	Orifice pressure differential, iwg
I	% isokinetics
M_n	Mass of collected particulate, mg
M_i	Mass emissions of species i, lb/hr
MW	Molecular weight of flue gas

MWi	Molecular weight of species i:
	NOx: 46
	CO: 28
	SO2: 64
	HC: 16
q	Sample time, minutes
ΔP	Average velocity head, iwg=($(\sqrt{\Delta P})^2$
P_{bar}	Barometric pressure, in. Hg Barometric pressure, in.Hg
P_s	Stack absolute pressure, in. Hg
P_{sg}	Stack static pressure, iwg
Q	Wet stack gas flow rate at actual conditions, wacfm
Q_{sd}	Dry stack gas flow rate at standard conditions, dscfm
SV	Specific molar volume of an ideal gas at std. Conditions, ft3/lb mole
T_m	Meter temperature, ^0R
T_{ref}	Reference temperature, ^0R
T_s	Stack temperature, ^0R
V_s	Stack velocity, ft/sec
V_{lc}	Volume of liquid collected in impingers, ml
V_m	Dry meter volume uncorrected, dcf
V_{mstd}	Dry meter volume at standard conditions, dscf
V_{wstd}	Volume of water vapor at standard conditions, scf
Y	Meter calibration coefficient

APPENDIX 2

Table A1 Table Analysis of coal used in the NIOSH tests

Ash Fusion (^{o}F)			
Initial		2600	
Softening		2640	
Hemi		2680	
Fluid		2740	
Ash Elemental Analysis (%)			
SiO_2		56.16	
Al_2O_3		31.54	
Fe_2O_3		2.78	
TiO_2		1.55	
P_2O_5		0.25	
CaO		1.16	
MgO		0.63	
Na_2O		0.18	
K_2O		1.48	
SO_3		0.23	
MnO_2	$<$	0.01	
	As 'R	Dry	DAF
Heating Value (Btu/lb)			
	13,341	13,739	14,881
Proximate Analysis (%)			
Moisture	2.9		
Ash	7.45	7.67	
Volitile Matter	37.73	38.86	42.09
Fixed Carbon	51.92	53.47	57.91
Ultimate Analysis (%)			
Hydrogen	5.33	5.16	5.59
Carbon	75.12	77.36	83.79
Nitrogen	0.59	0.61	0.66
Sulfur	0.64	0.66	0.71
Oxygen	10.87	8.54	9.25
Ash	7.45	7.67	

APPENDIX 3

Table A2 Analysis of coal used in the BBP tests

Air Dry Loss (%)	2.08		
Residual Moisture (%)	1.72		
Ash Fusion (oF)			
Initial	2650		
Softening	2720		
Hemi	2790		
Fluid	2800		
Ash Elemental Analysis (%)			
SiO_2		49.02	
Al_2O_3		27.95	
Fe_2O_3		8.25	
TiO_2		0.93	
P_2O_5		0.20	
CaO		4.34	
MgO		0.77	
Na_2O		0.15	
K_2O		0.20	
SO_3		2.86	
	Heating Value (Btu/lb)		
	13,202	21,287	123,383
Proximate Analysis (%)			
Moisture	3.76		
Ash	6.94	11.19	
Volitile Matter	37.98	61.24	354.95
Fixed Carbon	51.32	82.75	479.63
Ultimate Analysis (%)			
Hydrogen	5.40	1.90	46.56
Carbon	74.16	119.57	693.08
Nitrogen	1.35	2.18	12.62
Sulfur	0.96	1.55	8.97
Oxygen	11.19	12.65	73.34
Ash	6.94	11.19	

APPENDIX 4

Table A3 Mass Balance of NIOSH Run 1

Fuel(lb/hr)				Flue gas(lb/hr)							Comment:
	Coal Analysis (lb/lb)	**Na. Gas Analysis (lb/lb)**	**Mixed weight**	**O_2 Theo Reqd**	**CO_2**	**CO**	**O_2**	**N_2**	**H_2O**	**SO_2**	1.The composition of fuel: Coal 1580.4lb/hr
C to CO_2	74.83%	1182.7	3153.82	4320							2.Fuel heat Value coal 13341 Btu/lb
C to CO	0.29%	4.5	6.000		10.5						3.Exit temp of flue gas, t2=330F
C unburned		0									
H_2	5.01%	79.1	632.983					712.1			
O_2	8.29%	131.0	-131.0								
N_2	0.59%	9.3	4.320				5			8.1	4.Dry -bulb(ambient) temp: t1=48F
S	0.64%	10.1	9.2						18.4		
H_2O	2.90%	45.8						45.8			5. Rel humid=43%
ash	7.45%	117.7									
Sum	100.00%	1580.29	3675.3								
weight of flue gas			40524.2								6.pressure of H2O in air, A=Rel humid*Sat.Pressure
weight of O_2 in flue gas(excess air by lb)			5926.7			5926.7					7.Enthalpy of steam(100psi):1187Btu/lb
O_2(total), supplied by air=excess air +O_2 Ther Reqd			9602.0								8. Enthalp of feedwater(230F):198Btu/lb
N_2(total), supplied by air=29883.6-4.5			29591.5				29591				
Air(dry)=O_2(total)+N_2(total)			39193.5								9.Flowrate of steam(lb):17100 lb/hr
H_2O in air(bu) = dry air *A/(B-A)			43.8					44			10.Sat.Press.H20 at amb temp, in Hg 3.251
air(wet)=H_2O in air+air(dry)			39237.3								11. Barometric pressure, in.Hg,B=760
Flue gas constituents, total				4320.0	10.5	5926.7	29596	644.5	18.4	8.1	

APPENDIX 5

Table A4 Energy Balance of NIOSH Run 1

Flue gas constituents	**CO_2**	**CO**	**O_2**	**N_2**	**H_2O**	**SO_2**	**NO**	**Total**
Mcp,mean, t_2 to t_1	0.220	0.25	0.223	0.214	0.451	0.159	8.100	
In dry flue gas=mass each*Mcp*(t_2-t1)	2.7E+05	740.25	3.7E+05	2.E+06		8.3E+02	1.9E+04	2.4E+06
in sens heat, H_2O in air=weight H2O,M21 *Mcp*(t2-t1)					5570			5570
In sens heat, H_2O in fuel=(M4+M9+M10+M11)*Mcp*(t2-t1)					9.6E+04			9.6E+04
in latent heat,H_2O in fuel=(M4+M9+M10+M11)*1040					7.9E+05			7.9E+05
Total in wet flue gas								3322247
Due to unburned CO in flue gas=weight C to CO*9755								43898
Total flue gas losses+unburned combustible=P30+P31+P32								3366145
Heat from fuel combustion=weight of fuel(mixture)* heat content per lb								2.1083E+07
Heat adsorbed by steam								1.6912E+07
Heat loss								8.0455E+05
coefficency of boiler=Heat adsorbed by steam/Heat from fuel combustion								80.22%

APPENDIX 6

Table A5 Mass Balance of NIOSH Run (2+3)

Fuel			Flue gas(lb)								Comment:
	Coal Analysis (lb/lb)	Na. Gas Analysis (lb/lb)	Mixed weight	O_2 Theo Reqd	CO_2	CO	O_2	N_2	H_2O	SO_2	1.The composition of fuel:Coal & Construction wood 1649 lb/hr (2:1 in volume)
C to CO_2	62.10%	1202.4	3206.5	4394.8							2.Fuel heat Value:coal 11065 Btu/lb
C to CO	0.27%	3.8	5.1		9.0						3.Exit temp of flue gas,t2=330F
C unburned		0									
H_2	4.40%	85.0	680.1					765.1			
O_2	9.89%	191.4	-191.4								
N_2	0.73%	14.1	3.7				5.1			6.9	4.Dry -bulb(ambient) temp,t1=48F
S	0.78%	15.1	7.0						14.0		
H_2O	12.28%	237.5						237.5			5. Rel humid=43%
ash	9.55%	184.7									
											6. Barometric pressure, in.Hg,B=760
											7 .Sat.Press.H20 at amb temp, in Hg 3.2511
Sum	100.00%	1934.03	3711.0								
weight of flue gas			37963								8.pressure of H2O in air, A=Rel humid*Sat.Pressure
weight of O2 in flue gas(excess air by lb)			5868.4			5868					9.Enthalpy of steam(100psi):1187Btu/lb
O2(total), supplied by air=excess air +O2 Ther Reqd			9579.4								10. Enthalp of feedwater(230F):198Btu/lb
N2(total), supplied by air=29883.6-4.5			26594				26594				
Air(dry)=O2(total)+N2(total)			36174								
H2O in air(bu) = dry air *A/(B-A)			40.4					40			
air(wet)=H2O in air+air(dry)			36214								
Flue gas constituents, total				4394.8	9.0	5868.4	26599	1070.8	14.0	6.9	

APPENDIX 7

Table A6 Energy Balances of NIOSH Run (2+3)

Flue gas constituents	**CO_2**	**CO**	**O_2**	**N_2**	**H_2O**	**SO_2**	**NO**	**Total**
Mcp,mean, t2 to t1	0.220	0.25	0.223	0.214	0.451	0.159	6.934	
In dry flue gas=mass each*Mcp*(t2-t1)	2.7E+05	632	3.7E+05	1.6E+06		6.3E+02	1.4E+04	2.3E+06
in sens heat, H2O in air=weight H2O,M21 *Mcp*(t2-t1)					5141			5141
In sens heat, H2O in fuel=(M4+M9+M10+M11)*Mcp*(t2-t1)					1.3E+05			1.3E+05
in latent heat,H2O in fuel=(M4+M9+M10+M11)*1040					1.0E+06			1.0E+06
Total in wet flue gas								3426978
Due to unburned CO in flue gas=weight C to CO*9755								37458
Total flue gas losses+unburned combustible=P30+P31+P32								3464437
Heat from fuel combustion=weight of fuel(mixture)* heat content per lb								2.14E+07
Heat adsorbed by steam								1.66E+07
Heat loss								1.32E+06
coefficency of boiler=Heat adsorbed by steam/Heat from fuel combustion								77.64%

APPENDIX 8

Table A7 Mass Balance of NIOSH (4+5+6)

Fuel			Flue gas(lb)								Comment:
	Coal Analysis (lb/lb)	Mixed weight	O_2 Theo Reqd	CO_2	CO	O_2	N_2	H_2O	SO_2	NO	1.The composition of fuel:Coal 1416.5lb/hr
C to CO_2	74.84%	1091.5	2910.6	3987.4							2.Fuel heat Value:coal 13341 Btu/lb
C to CO	0.28%	4.0	5.3		9.337						
C unburned		0									3.Exit temp of flue gas,t2=330F
H_2	5.01%	73.0	584.2					657.3			
O_2	8.29%	120.9	-120.9								
N_2	0.59%	8.6	3.0				5.7			5.6	4.Dry -bulb(ambient) temp,t1=52F
S	0.64%	9.3	6.0						11.9		
H_2O	2.90%	42.3						42.3			5. Rel humidity=43%
ash	7.45%	108.6									
											6. Barometric pressure, in.Hg,B=760
Sum	100.00%	1458.30	3388.2								
weight of flue gas			34666								7 .Sat.Press.H20 at amb temp, in Hg 3.2511
weight of O_2 in flue gas(excess air by lb)			5672.3			5672					8.pressure of H2O in air, A=Rel humid*Sat.Pressure
O_2(total), supplied by air=excess air +O2 Ther Reqd			9060.5								9.Enthalpy of steam(100psi):1187Btu/lb
N2(total), supplied by air=29883.6-4.5			24245.1				24245				
Air(dry)=O_2(total)+N_2(total)			33305.6								10. Enthalp of feedwater(230F):202Btu/lb
H_2O in air(bu) = dry air *A/(B-A)			37.2					37			
air(wet)=H_2O in air+air(dry)			33342								11.Flowrate of steam(lb):16200 lb/hr
Flue gas constituents, total				3987	9.3	5672	24250	728.7	11.9	5.6	

APPENDIX 9

Table A8 Energy balance of NIOSH Run (4+5+6)

Flue gas constituents	CO_2	CO	O_2	N_2	H_2O	SO_2	NO	Total
Mcp,mean, t_2 to t_1	0.220	0.25	0.223	0.214	0.451	0.159	5.600	
In dry flue gas=mass each*Mcp*(t_2-t_1)	2.4E+05	648.9	3.5E+05	1.4E+06		5.3E+02	8.7E+03	2.0E+06
in sens heat, H_2O in air=weight H2O,M21 *Mcp*(t2-t1)					4667			4667
In sens heat, H_2O in fuel=(M4+M9+M10+M11)*Mcp*(t_2-t_1)					8.8E+04			8.8E+04
in latent heat,H_2O in fuel=(M4+M9+M10+M11)*1040					7.3E+05			7.3E+05
Total in wet flue gas								2862468
Due to unburned CO in flue gas=weight C to CO*9755								39034
Total flue gas losses+unburned combustible=P30+P31+P32								2901502
Heat from fuel combustion=weight of fuel(mixture)* heat content per lb								1.9455E+07
Heat adsorbed by steam								1.5725E+07
Heat loss								8.2859E+05
coefficency of boiler=Heat adsorbed by steam/Heat from fuel combustion								80.83%

APPENDIX 10

Table A9 Mass Balance of NIOSH Run (8+9)

Fuel				Flue gas(lb)							Comment:
	Coal Analysis(lb/lb)	**Mixed weight(lb)**	**O_2 Theo Reqd**	**CO_2**	**CO**	**O_2**	**N_2**	**H_2O**	**SO_2**	**NO**	1.The composition of fuel:Coal 1680 lb/hr
C to CO_2	61.94%	1135.4	3027.65	4140							2.Fuel heat Value: coal 12614 Btu/lb
C to CO	6.01%	6.3	8.368		14.64						
C unburned		0									
H_2	4.76%	80.0	639.7					719.7			3.Exit temp of flue gas,t2=330F
O_2	10.99%	184.6	-184.6								
N_2	0.51%	8.6	3.185				5.5			6.0	4.Dry -bulb(ambient) temp,t1=52F
S	0.70%	11.8	6.5						12.9		
H_2O	6.57%	110.4						110.4			5. Rel humid=43%
ash	8.52%	143.1									
Sum	100.00%	1680	3500								
weight of flue gas			36825								6. Barometric pressure, in.Hg,B=760
weight of O_2 in flue gas(excess air by lb)			5858			5858					7 .Sat.Press.H20 at amb temp, in Hg 3.2511
O_2(total), supplied by air=excess air +O_2 Ther Reqd			9359								8.pressure of H_2O in air, A=Rel humid*Sat.Pressure
N_2(total), supplied by air=29883.6-4.5			25783				25783				9.Enthalpy of steam(100psi):1187Btu/lb
Air(dry)=O_2(total)+N_2(total)			35142								10. Enthalp of feedwater(230F):198Btu/lb
H_2O in air(bu) = dry air *A/(B-A)			39.3					39			
air(wet)=H_2O in air+air(dry)			35182								11.Flowrate of steam(lb):15900 lb/hr
Flue gas constituents, total				4140.0	14.6	5858	25789	1004.4	12.9	6.0	

APPENDIX 11

Table A10 Energy Balance of NIOSH Run (8+9)

Flue gas constituents	CO_2	CO	O_2	N_2	H_2O	SO_2	NO	Total
Mcp,mean, t2 to t1	0.220	0.25	0.223	0.214	0.451	0.159	5.972	
In dry flue gas=mass each*Mcp*(t2-t1)	3.E+05	1018	3.6E+05	1.5E+06		5.7E+02	9.9E+03	2.2E+06
in sens heat, H_2O in air=weight H_2O,M21 *Mcp*(t2-t1)					4924			4924
In sens heat, H_2O in fuel=(M4+M9+M10+M11)*Mcp*(t2-t1)					1.0E+05			1.0E+05
in latent heat,H_2O in fuel=(M4+M9+M10+M11)*1040					8.6E+05			8.6E+05
Total in wet flue gas								3127822
Due to unburned CO in flue gas=weight C to CO*9755								61225
Total flue gas losses+unburned combustible=P30+P31+P32								3189048
Heat from fuel combustion=weight of fuel(mixture)* heat content per lb								2.0242E+07
Heat adsorbed by steam								1.5923E+07
Heat loss								1.1297E+06
coefficency of boiler=Heat adsorbed by steam/Heat from fuel combustion								78.66%

APPENDIX 12

Table A11 Mass Balance of BBP Run (1+2)

Fuel(lb/hr)					**Flue gas(lb/hr)**							**Comment:**
	Coal Analysis (lb/lb)	**Na. Gas Analysis (lb/lb)**	**Mixed weight**	**O_2 Theo Reqd**	**CO_2**	**CO**	**O_2**	**N_2**	**H_2O**	**SO_2**	**NO**	1.The composition of fuel Coal: 5071 lb/hr , Natural gas: 17,700 cuft/hr
C to CO_2	74.12%		3759	10025	13784							2.Fuel heat Value: coal 13202 Btu/lb Natural gas :23170 Btu/lb
C to CO	0.04%		2	2		4.175						
C unburned			0									3.Exit temp of flue gas, t2=609F
H_2	4.98%		253	2020					253			
O_2	7.85%		398	-398								
N_2	1.35%	1.22%	71	53				21			50	4.Dry -bulb(ambient) temp,t1=46F
S	0.96%		49	56						113		
ash	6.94%		352									5. Rel humid=35%
H_2O	3.76%		191						191			
CH_4		75.5%	645	2581	1775				1452			6. Barometric pressure, in.Hg,B=760
C_2H_6		23.3%	199	744	584				359			
Sum	100.00%	100%	5919	15083								7 .Sat.Press.H20 at amb temp, in Hg 3.2511
weight of flue gas				79006								8.pressure of H2O in air, A=Rel humid*Sat.Pressure
weight of O2 in flue gas(excess air by lb)				19330			19330					9.Enthalpy of steam:1196Btu/lb
O2(total), supplied by air=excess air +O2 Ther Reqd				34413								10. Enthalp of feedwater(235F):202Btu/lb
N2(total), supplied by air=3.76*O2(total)/32*28				36322				36322				
Air(dry)=O2(total)+N2(total)				70735								11.Flowrate of steam(lb): 53850 lb/hr
H2O in air(bu) = dry air *A/(B-A)				297					2.99E+02			
air(wet)=H2O in air+air(dry)				71033								
Flue gas constituents, total					16143	4.175	1.9E+04	36322	7044	113	49.86	

APPENDIX 13

Table A12 Energy Balance of BBP Run (1+2)

Flue gas constituents	CO_2	CO	O_2	N_2	H_2O	SO_2	NO	Total
Mcp,mean, t2 to t1	0.220	0.25	0.223	0.250	0.451	0.159	0.250	
In dry flue gas=mass each*Mcp*(t2-t1)	2E+06	587.6	1.3E+02	5E+06		1.0E+04	7018.4	7126751
in sens heat, H_2O in air=weight H2O,M21 *Mcp*(t2-t1)					75812			75812
In sens heat, H_2O in fuel=(M4+M9+M10+M11)*Mcp*(t2-t1)					5.7E+05			5.7E+05
in latent heat,H_2O in fuel=(M4+M9+M10+M11)*1040					2.3E+06			2.3E+06
Total in wet flue gas								10118729
Due to unburned CO in flue gas=weight C to CO*9755								17454
Total flue gas losses+unburned combustible=P30+P31+P32								1.01E+07
Heat from fuel combustion=weight of fuel(mixture)* heat content per lb								8.68E+07
Heat adsorbed by steam								53903850
Heat loss								2.27E+07
efficency of boiler=Heat adsorbed by steam/Heat from fuel combustion								62.13%

APPENDIX 14

Table A13 Mass Balance of BBP Run 6

Fuel(lb/hr)				Flue gas(lb/hr)								Comment:
	Coal Analysis (lb/lb)	Na. Gas Analysis (lb/lb)	Mixed weight	O_2 Theo Reqd	CO_2	CO	O_2	N_2	H_2O	SO_2	NO	1.The composition of fuel: Coal/wood 5753 lb/hr , Natural gas 18,700 cuft/hr
C to CO_2	67.34%		3874.3	10332	14206							2.Fuel heat Value:coal 11938 Btu/lb Natural gas :23170 Btu/lb
C to CO	0.03%	5753.4	1.7	2		4.1						3.Exit temp of flue gas: t2=615F
H_2	4.78%		275.0	2200					275			
O_2	10.31%		593.1	-593								
N_2	1.10%	1.22%	64.5	51				17			48	4.Dry -bulb(ambient) temp: t1=50F
S	0.80%		46.0	40						80		
ash	6.79%		390.6									5. Rel humid=35%
H2O	8.85%		509.1						509			
CH_4		75.5%	681.7	2727	1875				1534			6. Barometric pressure, in.Hg,B=760
C_2H_6		23.3%	210.4	786	617				379			
CO_2												7 .Sat.Press.H20 at amb temp, in Hg 3.2511
Sum	100.00%	100%	6646.7	15544								
weight of flue gas				70295								8.pressure of H2O in air, A=Rel humid*Sat.Pressure
weight of O_2 in flue gas(excess air by lb)				16995			16995					9.Enthalpy of steam(370F,175psi):1196Btu/lb
O_2(total), supplied by air=excess air +O_2 Ther Reqd				32539								10. Enthalp of feedwater(235F):202Btu/lb
N_2(total), supplied by air=3.76*O_2(total)/32*28				30452				3.1E+04				
Air(dry)=O_2(total)+N2(total)				62992								11.Flowrate of steam(lb):54000 lb/hr
H_2O in air(bu) = dry air *A/(B-A)				265					2.66E+02			
air(wet)=H_2O in air+air(dry)				63257								
Flue gas constituents, total					16698	4.1	1.70E+04	3.1E+04	6.00E+03	80.15	47.92	

APPENDIX 15

Table A14 Energy Balance of BBP test BP2-6

Flue gas constituents	CO_2	CO	O_2	N_2	H_2O	SO_2	NO	Total
Mcp,mean, t_2 to t_1	0.220	0.25	0.223	0.250	0.451	0.159	0.250	
In dry flue gas=mass each*Mcp*(t_2-t_1)	2.1E+06	575.76	1.3E+02	4.3E+06		7.2E+03	6.8E+03	6391516
in sens heat, H_2O in air=weight H_2O,M21 *Mcp*(t_2-t_1)					67753			67753
In sens heat, H_2O in fuel=(M4+M9+M10+M11)*Mcp*(t_2-t_1)					6.9E+05			6.9E+05
in latent heat,H_2O in fuel=(M4+M9+M10+M11)*1040					2.8E+06			2.8E+06
Total in wet flue gas								9951375
Due to carbon in refuse =line()*14100								17041
Due to unburned CO in flue gas=weight C to CO*9755								9.97E+06
Total flue gas losses+unburned combustible=P30+P31+P32								8.96E+07
Heat from fuel combustion=weight of fuel(mixture)* heat content per lb								54054000
Heat adsorbed by steam								2.56E+07
efficency of boiler=Heat adsorbed by steam/Heat from fuel combustion								60.32%

APPENDIX 16

Table A15 Mass Balance of BBP Run (3+4)

Fuel (lb/hr)				Flue gas (lb/hr)								Comment:
	Coal Analysis (lb/lb)	**Na. Gas Analysis (lb/lb)**	**Mixed weight**	**O_2 Theo Reqd**	**CO_2**	**CO**	**O_2**	**N_2**	**H_2O**	**SO_2**	**NO**	1.The composition of fuel: Coal 3608 lb/hr, Natural gas: 11,800 cuft/hr
C to CO_2	74.14%		2670.1	7120.3204	9790.4							2.Fuel heat Value: coal:13202 Btu/lb Natural gas: 23170 Btu/lb
C to CO	0.02%	3608.752	6.13	1.531		14.3						3.Exit temp of flue gas: t2=557F
H_2	4.98%		179.7	1437.8					180			
O_2	7.85%		283.3	-283.3								
N_2	1.35%	1.22%	55.1	41.44				16			39	4.Dry -bulb(ambient) temp: t1=46F
S	0.96%		34.64	54						108		
ash	6.94%		250.4									5. Rel humid=35%
H2O	3.76%		135.6						136			
CH_4		75.5%	430.1	1720.8	1183.02				968			6. Barometric pressure, in.Hg,B=760
C_2H_6		23.3%	132.7	495.8	389.535				239			
CO_2												7 .Sat.Press.H20 at amb temp, in Hg 3.2511
Sum	100.00%	100%	4178.2	10588.5								
weight of flue gas				90143.5								8.pressure of H2O in air, A=Rel humid*Sat.Pressure
weight of O_2 in flue gas(excess air by lb)				2.956E+04			29561					9.Enthalpy of steam:1196Btu/lb
O_2(total), supplied by air=excess air +O_2 Ther Reqd				4.01E+04								10. Enthalp of feedwater(235F):202Btu/lb
N_2(total), supplied by air=3.76*O_2(total)/32*28				4.4464E+04				44464				
Air(dry)=O_2(total)+N2(total)				8.46E+04								
H_2O in air(bu) = dry air *A/(B-A)				3.55E+02					3.6E+02			11.Flowrate of steam(lb):36500 lb/hr
air(wet)=H_2O in air+air(dry)				8.50E+04								
Flue gas constituents, total					11363	14.3	2.96E+04	44464	4594	108	39	

APPENDIX 17

Table A16 Energy Balance of BBP Run (3+4)

Flue gas constituents	CO_2	CO	O_2	N_2	H_2O	SO_2	NO	Total
Mcp,mean, t_2 to t_1	0.220	0.25	0.223	0.250	0.451	0.159	0.250	
In dry flue gas=mass each*Mcp*(t_2-t_1)	1.3E+06	2.E+03	1.1E+02	5.7E+06		8.8E+03	4964	6971113
in sens heat, H_2O in air=weight H_2O,M21 *Mcp*(t_2-t_1)					82311			82311
In sens heat, H_2O in fuel=(M4+M9+M10+M11)*Mcp*(t_2-t_1)					3.5E+05			3.5E+05
in latent heat,H_2O in fuel=(M4+M9+M10+M11)*1040					1.6E+06			1.6E+06
Total in wet flue gas								8987645
Due to unburned CO in flue gas=weight C to CO*9755								59803
Total flue gas losses+unburned combustible=P30+P31+P32								9.05E+06
Heat from fuel combustion=weight of fuel(mixture)* heat content per lb								6.09E+07
Heat adsorbed by steam								36536500
Heat loss								1.53E+07
efficency of boiler=Heat adsorbed by steam/Heat from fuel combustion								60.04%

APPENDIX 18

Table A17 Mass Balance of BBP test BP2-7

Fuel(lb/hr)				Flue gas(lb/hr)								Comment:
	Coal Analysis (lb/lb)	Na. Gas Analysis (lb/lb)	Mixed weight	O_2 Theo Reqd	CO_2	CO	O_2	N_2	H_2O	SO_2	NO	1.The composition of fuel:Coal/wood 4136 lb/hr , Natural gas 11,300 cuft/hr
C to CO_2	67.34%		2786	7429	10214.5							2. Blend Fuel heat Value:coal 11938 Btu/lb Natural gas :23170 Btu/lb
C to CO	0.03%		3	2		6.587						3.Exit temp of flue gas,t2=561F
H_2	4.78%		198	1582					198			
O_2	10.31%		426	-426								
N_2	1.10%	1.22%	48	41				10			38	4.Dry-bulb(ambient) temp,t1=50F
S	0.80%		33	17						34		
ash	6.79%		281									5. Rel humid=35%
H2O	8.85%		366						366			
CH_4		75.5%	637	2549	1752				1434			6. Barometric pressure, in.Hg,B=760
C_2H_6		23.3%	197	734	577				354			
CO_2												7 .Sat.Press.H20 at amb temp, in Hg 3.2511
Sum	100.00%	100%	4974.4	11927								
weight of flue gas				57077								8.pressure of H2O in air, A=Rel humid*Sat.Pressure
weight of O_2 in flue gas(excess air by lb)				16587			16587					9.Enthalpy of steam: 1196Btu/lb
O_2(total), supplied by air=excess air +O_2 Ther Reqd				28514								10. Enthalp of feedwater(235F): 202Btu/lb
N_2(total), supplied by air=3.76*O_2(total)/32*28				23521				2.4E+04				
Air(dry)=O_2(total)+N2(total)				52035								
H_2O in air(bu) = dry air *A/(B-A)				219					2.2E+02			11.Flowrate of steam(lb): 36900 lb/hr
air(wet)=H_2O in air+air(dry)				52255								
Flue gas constituents, total					12544	6.587	1.66E+04	2.4E+04	4.3E+03	34.1	38.1	

APPENDIX 19

Table A18 Energy Balance of BBP test BP2-7

Flue gas constituents	CO_2	CO	O_2	N_2	H_2O	SO_2	NO	Total
Mcp,mean, t_2 to t_1	0.220	0.25	0.223	0.250	0.451	0.159	0.250	
In dry flue gas=mass each*Mcp*(t_2-t_1)	1.4E+06	841.49	102	3.0E+06		2.8E+03	4863	4422932
in sens heat, H_2O in air=weight H_2O,M21 *Mcp*(t_2-t_1)					50619			50619
In sens heat, H_2O in fuel=(M4+M9+M10+M11)*Mcp*(t_2-t_1)					5.4E+05			5.4E+05
in latent heat,H_2O in fuel=(M4+M9+M10+M11)*1040					2.4E+06			2.4E+06
Total in wet flue gas								7461414
Due to carbon in refuse =line()*14100								27538
Due to unburned CO in flue gas=weight C to CO*9755								7.49E+06
Total flue gas losses+unburned combustible=P30+P31+P32								6.20E+07
Heat from fuel combustion=weight of fuel(mixture)* heat content per lb								36936900
Heat adsorbed by steam								1.76E+07
efficency of boiler=Heat adsorbed by steam/Heat from fuel combustion								59.55%

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